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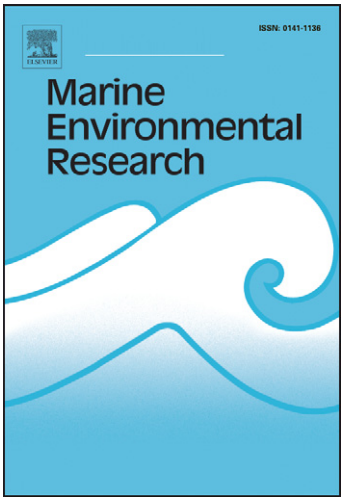

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A review of subtidal benthic habitats and invertebrate biota of the Strait of Georgia, British Columbia

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Abstract

The initial phase of a collaborative Ambient Monitoring Program (AMP) for the Strait of Georgia (SoG) (Marine Environmental Research Vol. x, pp.) has focused on the benthos, sedimentary regimes, organic and contaminant cycling in subtidal regions of the strait. As part of that project, we review the primarily subtidal benthic invertebrate faunal communities found in the SoG, with particular reference to habitats and sediment conditions. This topic has not been addressed in the primary literature for over 20 years. Benthic biota are the baseline sentinels of the influence of natural and anthropogenic inputs to sediments. They are also a fundamental component of the food chain at the seafloor, and their community ecology must be clearly understood in order to predict how anthropogenic activities and climate change will affect our coastal oceans. The purpose of this review is to provide context on habitats and biota in the SoG, and to highlight topics and geographic areas where our knowledge of the benthos is limited or lacking.

Keywords: benthos; Strait of Georgia; subtidal communities; intertidal communities; British Columbia; anthropogenic influences

1. Introduction

The introduction (Section 1) includes the background to this review (Section 1.1), plus overviews of the oceanography (Section 1.2) and sedimentary regimes (Section 1.3) of the SoG. Section 2 reviews information available on the SoG's benthic habitats and invertebrate

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communities, with specific sections on intertidal (Section 2.1) and subtidal (Section 2.2) communities and habitats. Section 2.2 is further divided into subsections based on subtidal depth range and substrate type. Anthropogenic influences on benthic environments and invertebrates of the SoG are summarized in Section 3; case studies of each type of anthropogenic influence are also presented. Section 4 provides a brief summary of the review paper.

1.1 Background

Sources, and availability, of information for this review depended largely on the depth range of interest. For example, one source of information on intertidal habitats and biotic conditions for the SoG includes broad-scale mapping, or monitoring, studies with the purpose of managing broader geographic regions for multi-user inputs and conservation. Mapping data are limited to intertidal zone and the shallow subtidal (<30 m) habitats that have broad aerial, or ground survey coverage. Unfortunately, at depths >30 m, such mapping and survey data do not exist for the SoG. Rather, information for these depths comes primarily from ship-board sampling as part of studies designed to address specific questions for limited geographic areas. These studies tend, therefore, to be focused on a defined area, a specific anthropogenic influence and/or on data collection in support of fisheries and/or environmental management. Similar sources of information are also available for intertidal and shallow subtidal (0-30 m) habitats for the SoG. While most marine habitats are discussed, at least briefly, in this review, the paper was conceived within the context of a project which was biased towards subtidal, sedimentary habitats, and hence it is these latter habitats that are the focus of this review.

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In temperate coastal areas world-wide, most benthic biological research and monitoring programs focus on macrobenthic invertebrates (those captured with >500 µm mesh screens). For this reason, macrobenthic invertebrate communities are the main subject of this review. In addition to size, the life histories, responses to natural and anthropogenic conditions and changes, and trophic strategies of macrobenthic invertebrates are far better understood and documented than those of smaller invertebrates and protozoans. For example, many commercially important macroinvertebrate species live within the sediments (e.g., clams) or on the surface of the sediments or hard substrata (e.g., crabs). In addition, benthic macroinvertebrates have often been the subject of antropogenic impact studies; as a result of being largely sedentary, these organisms are exposed to ambient conditions and may serve as the first-line sentinels reflecting localized impacts (c.f. Warwick and Clark, 1993; Pohle et al., 2001). It should be noted that many benthic macroinvertebrates have a pelagic larval development stage and, as a result, are part of an extensive and intricate food chain which is not limited to the benthos but which can extend throughout the water column.

Benthic invertebrates process the particulate, organic materials (detritus, small organisms) that are deposited on the seafloor or that are suspended within reach of the organisms, using a wide range of feeding strategies such as deposit feeding, suspension feeding, filter feeding, or scavenging. Benthic invertebrates may also be predators, herbivores (grazing on living plant material) or they may rely, at least partially, on chemoautotrophy via symbioses with bacteria for their nutrition (Barnes, 1987). Schwinghamer (1983) estimated that, in soft sediments in temperate coastal regions, macroinvertebrates constitute approximately 95% of the total invertebrate biomass. Similarly, Rowe et al. (1991) found that in coastal areas in global

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temperate regions, benthic macroinvertebrates tend to dominate the benthic biomass (excluding fish) in mid-depth subtidal areas (i.e. below the euphotic zone) followed by the other two major benthic consumer groups, the meiofauna (interstitial invertebrates sized 42 µm to 1 mm) and the single-celled organisms (primarily bacteria). While single-celled organisms are beyond the scope of this review, meiofaunal community studies, where applicable, have been incorporated. With the exception of foraminifera (for which taxonomy based on shell morphology has been extensively used in modern and ancient sediments for interpolation of biological and environmental conditions), however, the availability of information on meiofaunal taxonomy, life histories, and environmental tolerances is limited.

In contrast to diversity and biomass patterns, Schwinghamer (1981) estimates that, because of their small size, approximately 95% of the total abundance of benthic invertebrates consists of nematodes and harpacticoid copepods. Included in this total abundance estimate are the larvae of larger invertebrates and a series of less common phyla, typically captured only by 63 µm mesh screens, which prey on benthic bacteria, flagellates, ciliates, foraminifera, and diatoms or blue-green algae in shallower muds (Schwinghamer, 1981; Gerlach et al., 1985). The importance of meiofauna as the base heterotrophs in the food chain varies depending on habitat type and depth (Coull and Bell, 1979). Certainly, components of the meiofauna can be very important in intertidal, and shallow subtidal (i.e. photic zone) benthos where there is considerable primary production occurring in the sediments (Schwinghamer, 1981, 1983; Rowe et al., 1991). Copepods, in particular, can be a vital food resource for juvenile fish in near-shore nursery areas (for review see Tito de Morais and Bodiou, 1984). Harpacticoid copepods in sediment core samples from *Zostera marina* beds in the Nanaimo River Estuary and the Cowichan Estuary were diverse (over 50 species from the Nanaimo River Estuary) and abundant (Levings et al.,

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1983). In contrast to their global findings for mid-depth subtidal coastal areas, Rowe et al. (1991) suggest that meiofauna may be a more important component of deep subtidal biomass than are macroinvertebrates. In the SoG, a moderately deep coastal area, it is reasonable to assume, therefore, that benthic macroinvertebrates are the primary consumers at the base of the (benthic) food chain and are more important than meiofauna in this regard.

The SoG is part of the broader coastal region of southwest BC and northwest Washington State. Therefore, biological reference materials for the Pacific northwest (e.g. Carefoot 1977; Kozloff 1987) have general applicability to the SoG. The most recently published review of the benthos of the SoG is Levings et al. (1983). This review included reference to broad-scale, historical biological surveys from the 1960s and 1970s that were based primarily in intertidal and shallow subtidal areas; at the time of the review, there was very little available research on mid-subtidal to deep subtidal benthic invertebrate fauna. These surveys included a few studies of soft substrate infaunal invertebrates (Ellis, 1967a, b, 1968a, b, c) and descriptions of an extensive trawl survey of larger epifauna (Bernard 1978). A general description of fjord cliff fauna, based on submersible surveys from three contiguous fjords, was also included in the review of Levings et al. (1983). Although not included in the subject matter of this review, intertidal research on algal and marine vascular plant communities in the SoG was reviewed by Levings et al. (1983) and, more recently, by Watson (1998). In addition to the general lack of research on subtidal invertebrate fauna, Levings et al. (1983) point out that there were no data at all from the deep basin of the SoG and also that little was known about the type, source or composition of sediments, or sedimentation rates, in the SoG. In the past twenty-five years, a great deal of effort has been expended to map biophysical conditions in the substrates of the intertidal and shallow subtidal zones in the SoG; this information is reviewed in Sections 2.1 and 2.2. However, this

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review concentrates, primarily, on the less accessible and less well understood, subtidal regions of the SoG.

From 1986 to 1992, a series of primarily deeper (>30 m) subtidal benthic surveys were conducted by the Canadian Department of Fisheries and Oceans and Environment Canada in the SoG and surrounding areas (Burd and Brinkhurst, 1990; Cross and Brinkhurst, 1991; Burd and Brinkhurst, 1992). Only one study, carried out in Boundary Bay, conducted both intertidal and shallow subtidal benthic surveys (Burd et al., 1987). These surveys were briefly referred to in Brinkhurst et al. (1994) and Watson (1998). The original data, and a meta-analysis for these coastal surveys, are provided in Burd (1992).Wilson et al. (1994) edited a trans-boundary (Canada-USA) symposium report reviewing the marine environment and biota of the SoG, Puget Sound and Juan de Fuca Strait. Several research papers from this report are included in this review. A broadly based trans-boundary trawl survey of macroinvertebrates and bottom fish species, which included the southern SoG (Canadian and US), was conducted in 2001 by the Washington State Department of Fish and Wildlife (Palsson et al., 2003). Although 117 taxa of large invertebrates were enumerated from trawls, the focus of the survey was on fish stocks, historical trends, and exploitation rates. However, the distributions of commercial invertebrates (notably Dungeness crab and pandalid shrimp) were highlighted.

Aside from a small number of government studies focused on historical environmental issues (e.g. the Brittania Mine in Howe Sound (G3 Consulting, 2003; Hagan et al., 2004; Levings et al., 2004; Zis et al., 2004), the remaining benthic subtidal habitat and invertebrate sampling has been carried out, primarily, as part of monitoring programs (data collection either for establishing a

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baseline or as part of an ongoing program) related to specific anthropogenic inputs into the SoG or its fjords.

Much of the benthic infaunal data available from the SoG since 1986 has been collated into a taxonomically coded and consistent meta-database which includes data from background (or reference) areas, data from areas of known anthropogenic input, and accompanying sediment physical and geochemical data (Burd et al., in press). Burd et al. (in press) also provide a detailed discussion of the biotic responses of benthic invertebrate communities in the SoG to sedimentation rate and organic flux.

1.2. Oceanography

The oceanography of the SoG, and a number of surrounding fjords and inlets, is described by Thomson (1981), LeBlonde (1983), Crean et al. (1988), and Stacey et al. (1991), with updates by Thomson (1994, 1998), Li et al. (1999), and Masson and Cummings (2004). Early numerical tidal current models for the SoG were reported by Thomson (1981) and Crean et al. (1988); more recent tidal current models are described in Foreman et al. (1995, 2004). Models of current variability due to wind, river discharge (estuarine circulation), winter cooling and other non tidal factors, as well as bio-physical aspects of the water column variability, are currently being developed by scientists at the University of British Columbia, (through the STRATOGEM project (http://www.stratogem.ubc.ca/), the University of Victoria (VENUS project; http://www.venus.uvic.ca/index.html) and the Canadian Department of Fisheries and Oceans Institute of Ocean Sciences (IOS) (Masson and Cummings, 2004).

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The SoG is 222 km long and approximately 28 km wide with a mean depth of roughly 155 m (Thomson, 1981; Davenne and Masson, 2001). Additional characteristic features of the SoG, taken from England et al. (1996), Thomson (1998), and Thomson and Foreman (1998) are summarized in Table 1. Fig. 1 shows the depth topography, sills and surrounding inlets of the Strait.

The two primary components of circulation in the SoG, and the dominant factors determining the rate of basin flushing and exchange, are the diurnal and semidiurnal tidal currents and the seasonally variable estuarine circulation driven by fresh water fluxes into the strait. The strength of estuarine circulation in the SoG is affected seasonally by the volume of runoff discharge from the major rivers (mainly the Fraser River) which enter mostly in late spring to early summer, with a secondary surge in late fall. Estuarine circulation is strongly affected by the intensity of vertical tidal mixing which becomes maximal in the narrow channels leading into the strait. Winds, surface heating and cooling, intrusions from adjoining Juan de Fuca Strait and Discovery Passage, and variations in offshore oceanic conditions also affect the circulation in the strait. Other factors influencing the circulation are the shape of the coastline and slope of the bottom topography, bottom and internal friction, inertial forces and external factors related to up-strait propagation of oceanic "events" originating over the outer continental margin. These factors are discussed in Thomson (1998) and outlined in detail in Griffin and LeBlonde (1990), Thomson (1994), and Thomson et al. (2007). Detailed discussion on the estuarine circulation in the SoG can be found in Marinone and Pond (1996), Li et al. (1999), Pawlowicz (2001) and Masson (2002).

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There are a number of distinct oceanographic regimes in the SoG (Thomson, 1998). These include the three main basin oceanographic regimes (delineated in Fig. 1) that are described by Thomson (1981, 1998) as follows:

1) the Southern SoG, which has vigorous flow exchange and mixing between the southern channels (Haro Strait and Rosario Strait) and the main body of the Strait;
2) the Central SoG, which extends northward to the southern end of Texada Island, and receives the main volume of fresh water from the Fraser River runoff; and
3) the Northern SoG, which occupies the northern portion of the Strait (from the southern end of Texada Island northwards) but excludes the margin along the eastern side of Vancouver Island where the water properties appear to be strongly affected by the southward density jet entering through Seymour Narrows on the flood tide.

Connecting oceanographic regimes include Juan de Fuca Strait, which extends from the Pacific continental shelf to the entrance to the southern end of Haro and Rosario straits (two tidally active channels with very similar temperature and salinity structure (Thomson, 1998). The northern end of the SoG is connected to the Pacific Ocean through Discovery Passage and Johnstone Strait (Harrison and Yin, 1998). These oceanic connections at the northern and southern ends of the SoG have strong tidal flow and intense turbulent mixing, which is further enhanced through the narrow adjoining channels (Thomson, 1981). At the southern end of the SoG, for example, a complex topography of islands and sills creates strong vertical and lateral tidal mixing (Masson and Cummings, 2000; Pawlowicz, 2002; Thomson et al., 2007), which is also evident in the vertically mixed particulate distributions in this region (Johannessen et al., 2005b). There is nominal surface outflow at both ends of the SoG, with approximately 85-95%

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of the flow volume through Haro and Rosario straits and the remaining flow through Johnstone Strait. Thomson (1981) examined the cross-sectional areas of all channels leading into the SoG and found that the southern channels account for 93% of the cross-sectional area and the northern channels only 7%. The major inlets adjoining the SoG are Burrard Inlet, Howe Sound, Jervis Inlet (including Sechelt Inlet), Bute Inlet and Saanich Inlet (Harrison and Yin, 1998). Knight Inlet and Toba Inlet connect through a northern island-strewn archipelago, so can be considered a separate oceanographic regime. Surface outflow of riverine water strongly affects the water property structure in this region (Thomson, 1998).

The southern SoG is defined as the area extending south from the main arm of the Fraser River to the eastern end of Juan de Fuca Strait (Thomson, 1981; Harrison and Yin, 1998; Thomson, 1998). This oceanographic regime is dominated by the Fraser River plume when it moves southward (e.g. during northwest winds and an ebb tide) and is significantly influenced by tidal mixing over the shallow sills of Rosario and Haro straits during spring tides. Tidal mixing injects nutrient-rich water into the southern Strait which lessens the occurrence of nitrogen limitation episodes in the summer. It is, therefore, considered a highly productive area even though it has not been well studied (Harrison and Yin, 1998). Haro Strait, which separates the southern Gulf Islands and Vancouver Island from the San Juan Islands, is the most important of these channels. The flow exchange through this channel is strongly three-dimensional, with variation over multiple time scales (Pawlowicz, 2002). The exchange undergoes marked variability at fortnightly, monthly and seasonal time scales due to corresponding variations in the intensity of the tidal mixing in the channels (i.e., the hydraulic control mechanism outlined by Griffin and LeBlonde, 1990). During the neap tide portion of the fortnightly cycle, when the

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tidal currents in Haro Strait are minimal, surface brackish waters from the SoG are able to "slide" seaward over the more dense oceanic waters entering at intermediate to near-bottom depths from Juan de Fuca Strait. In summer (July to October), the deep estuarine inflow in Juan de Fuca Strait carries warm, salty (high density), low-oxygen, high nutrient water inward from the coastal ocean. This water is then able to penetrate to the bottom of the SoG in a series of monthly pulses, renewing the deep water nutrient levels in the region; in winter (November to March), this subsurface inflow occurs only to intermediate depths (Masson and Cummings, 2004). Deep water oxygen levels are increased during deep water intrusions of cold highly oxygenated water in spring. During the spring tidal portion of the fortnightly cycle, when tidal currents are maximal, turbulent vertical mixing in Haro Strait and other passages prevents the simple exchange of brackish SoG water with deeper oceanic water. In this case, there is a reflux of water from the passages back into the SoG at intermediate depths. Additional details on the exchange processes through Haro Strait are found in Griffin and LeBlonde (1990), Thomson (1994), Pawlowicz (2002), Masson and Cummings (2004), and Thomson et al. (2007).

The central SoG is defined herein as the area from the south end of Texada Island to a line drawn from Point Roberts to the Saanich Peninsula (Waldichuk, 1957; Thomson, 1981, 1998). This oceanographic regime is complex due to the seasonal influences of the Fraser River plume, which is characterized by low salinity, very high light-extinction coefficients, high SiO_4^{-4}, low chlorophyll and low primary productivity. During freshet, the sediment-laden surface plume is 2-10 m thick (Thomson, 1981), thus reducing the depth of the euphotic zone and primary production within the surface waters, while greatly enhancing primary (Stockner et al., 1979) and secondary (Mackas and Louttit, 1988) production at the plume margins. Surprisingly,

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chlorophyll levels and the abundance of zooplankton and fish are frequently high under the plume (Harrison and Yin, 1998). Bacterioplankton production is greatly enhanced within the brackish plume water (Albright, 1983). The area of the Fraser River plume undergoes marked seasonal variability, with the maximum variations in extent, as well as chemical and biological parameters, occurring in June, at which time the plume can dominate the central SoG. At any given time, the distribution of the plume is influenced by the stage of the tidal currents (flood verus ebb tide) and by surface wind speed and direction (Harrison and Yin, 1998). After wind and tidal mixing, the third largest mechanism for transporting deep nutrient inputs into the surface layer of the SoG is the entrainment of nitrate-rich salt-wedge water directly into the base of the Fraser River outflow (Harrison and Yin, 1998). Seasonal cycles in nutrients, chlorophyl and primary productivity are relatively predictable in the central SoG (Harrison et al., 1983) but the day-to-day variation is high, with values ranging over one order of magnitude in some months (e.g. June). Nitrogen limitation frequently occurs in July and August, depending on the magnitude of the wind events. As a consequence, it is difficult to draw a reliable map of annual primary productivity for the SoG (Harrison and Yin, 1998). Modelling surface layer productivity is also a major component of the STRATOGEM project (http://web.uvic.ca/~dower/dowerlab/research.html).

As with the southern passages, flow through the northern passages of Discovery Passage and Johnstone Strait is strongly tidal with a pronounced estuarine circulation component driven by runoff from the Fraser River. Hydraulic processes again modify the fortnightly, monthly and seasonal exchange of waters through this region. Although the flow dynamics in the northern passages are similar to those in the southern passages, the flow tends to have a weaker cross-

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channel component and experiences less variability in water properties due to the greater narrowness of the channels (Thomson, 1981, 1994). Considerable oceanographic information is available for this region as a result of current and water property surveys conducted in the region in the 1970s. For data on currents and estuarine-type circulation see Thomson (1976, 1977), Huggett et al. (1980), Thomson and Huggett, (1980), and Thomson et al. (1980a, b). Haigh and Taylor (1991) studied microplankton communities in the northern SoG and determined that, because of the long wind fetch and weak halocline (relatively little influence of the Fraser River compared to the southern regions), wind mixing is likely to prolong or prevent pronounced bloom formation. By late summer, the west side of the SoG is diatom-dominated and more productive due to a nutrient-rich tidal jet flowing out of Discovery Passage during a flood tide. The east side is more stratified due to surface heating and a somewhat lower salinity due to the Fraser River plume (mainly in June and July) (Haigh and Taylor, 1991).

The fjords adjoining the SoG represent a separate oceanographic domain due to the relative isolation of their water masses from the rest of the strait (Thomson, 1998). The mainland fjords include Howe Sound, Jervis Inlet, Bute Inlet, Toba Inlet, Knight Inlet, and Saanich Inlet (the latter being the only fjord on the eastern side of Vancouver Island). Toba and Knight inlets are not always considered to be part of the SoG (Harrison and Yin, 1998). All fjords are separated from the main basin by sills shallower than the fjord basin. Only Burrard Inlet, discussed later in this section, lacks a sill and is not a fjord. Behind the sills, the fjords have glacially-carved basins which are often far deeper than the SoG itself; the deepest fjord basin (700 m) is found in Jervis Inlet. Tidal and estuarine currents over the sills provide for an exchange of material with the SoG, including the possibility of intermittant deep-water exchange events dependent on

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conditions inside and outside of the silled basins. The sill regions are characterized by enhanced tidal currents due to restricted openings and shallow depths; this is particularly true in Knight Inlet (Farrow et al., 1983; Tunnicliffe and Wilson, 1988) and at the famous Skookumchuk Narrows opening into Jervis Inlet (Thomson, 1981). However, inlets with especially shallow sills at the mouth tend to have low bottom currents in the deep basins located behind the sill, which can lead to stagnation resulting in low dissolved oxygen levels in bottom waters and sediments (Thomson, 1981). Basic features of basin topography and oceanography for the SoG fjords are described by D. Stucchi (IOS, Sidney, BC) (http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/default_e.htm).

Saanich Inlet, the best studied of the SoG inlets in terms of sediments (note that this is not true with respect to physical oceanography, where Knight Inlet is better understood), is smaller than most of the mainland fjords and has a relatively minor freshwater input but a substantial freshwater source just outside the sill (Cowichan River). The Inlet has a shallow sill at 70 m depth and a maximum basin depth of 225 m. Saanich Inlet is unique in that it is the only marine fjord in the SoG system with bottom water (>120-140 m) that is anoxic for most of the year. These conditions are due to high primary production, in addition to restricted bottom water exchange that occurs over extremely limited duration (Gargett et al., 2003). During fall upwelling conditions, Saanich Inlet bottom waters are oxygenated for a short time interval only, with anoxic conditions returning rapidly and extensively throughout the deep waters and sediments (Anderson and Devol, 1973). Fall upwelling in the SoG usually pushes the bottom anoxic layer up to mid-water depths prior to complete flushing. Deep water renewal in Saanich Inlet is described in detail by Anderson and Devol (1973).

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Howe Sound, a fjord located just north of Vancouver, has the second largest freshwater discharge into the SoG. The Squamish River, along with the Cheakamus River and some input from the Fraser River plume, creates low surface salinities in the head of the fjord, along with a strongly stratified water column with moderate oxygen in the top 30 m. These conditions, in combination with the heavy glacial silt load carried by the Squamish River from May to September, result in a high, near-surface, suspended silt load and brackish surface layer that greatly restrict light penetration (McDaniel, 1973; Hoos and Vold, 1975). Similar conditions are present in other glacially-fed fjords, such as Bute Inlet and Knight Inlet, although fresh water input is lower in these latter two fjords (http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/references_e.htm). Deep water (>180 m) in Howe Sound tends to be seasonally hypoxic, with flushing of bottom water occurring at the time of seasonal upwelling (Levings, 1980a, b).

Knight Inlet has a maximum depth of 540 m and two basins; the sill to the inner basin is located at 48 m depth and the sill to the outer basin, at the mouth of the inlet, at 60 m depth. Bottom water oxygen levels are higher than most of the mainland fjords (~3 ml/L), indicating frequent renewals and exchange of a large fraction of the deep water (http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/knight_inlet_e.htm). Bute Inlet has a maximum depth of 650 m, with a relatively deep sill at 370 m depth and good bottom water oxygenation and renewal. Bute Inlet has two rivers at the head, with mainly glacial sedimentation (D. Stucchi, (http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/ references_ e.htm).

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As noted earlier, the deepest mainland fjord is Jervis Inlet, with a maximum depth of 670 m. The sill to the outer basin in Jervis Inlet is relatively deep (240 m) and bottom water exchange is sufficient to maintain reasonable oxygen levels in the deep basin all year. This inlet also has the lowest freshwater input of all the mainland fjords (D. Stucchi, http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/ references_ e.htm). The oceanographic energetics of Jervis Inlet are described by Freeland and Farmer (1980). Haigh et al. (1992) and Taylor et al. (1994) described the seasonal cycle of temperature, salinity, nutrients, chlorophyll, and phytoplankton species for Sechelt Inlet, an arm of Jervis Inlet. Sechelt Inlet is composed of the well mixed Skookumchuck Narrows, and the more stratified waters of the main inlet and Salmon Inlet.

Burrard Inlet, composed of Vancouver Harbour, Indian Arm and Port Moody Arm, receives moderate runoff from the Indian River, with the outer section of the inlet influenced by the Capilano and Seymour Rivers (Harrison and Yin, 1998). Burrard Inlet is located within the Greater Vancouver Regional District and is the most heavily industrialized inlet in British Columbia. The inlet has a maximum depth of 90 m and the main basin, as well as the shallow, isolated arms, are well oxygenated throughout the year and flush rapidly (Levings and Samis, 2001; Stacey and Pond, 2003). During a large part of the phytoplankton growing season (May to July), high-silt water from the Fraser River decreases light penetration in the surface layer and hence, primary productivity is reduced (Harrison and Yin, 1998). Although it does not have a sill at the mouth, Burrard Inlet does have several constrictions within the Inlet which create high currents (Thomson, 1981). Partially as a result of the lack of sill, fine silt sediments in the outer inlet flow out into the main basin of the SoG. Indian Arm, located at the far northeastern end of Burrard Inlet, is more fjord-like in structure with a 220 m deep basin and a shallow sill (15 m to 25 m).

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1.3. Sedimentary Regime

1.3.1 Shoreline Description

For the SoG, both the total shoreline length inclusive of fjords (3721 km), and the area of benthic habitat (substrate) types were estimated by Levings et al. (1983). The authors note that, for their estimates, data from hydrographic charts on bottom type was sufficiently detailed only for intertidal and subtidal habitats down to 20 m. The authors use "shoreline" to represent intertidal and subtidal habitats down to 20 m and note that rocky and sandy shores make up 88% of the total shoreline length. However, when area is calculated, sand and mud substrates account for 66.8% (832 km^2) of the total 1245 km^2 of intertidal and shallow subtidal habitats. In contrast, rocky shores contribute only 320 km^2 or 25.7% to the total area. Using Natural Resources Maps, Levings et al. (1983) computed subtidal areas at depths >20 m. While only 11% of the subtidal area of the SoG is in the 20-50 m depth range, approximately 71% of the subtidal area is within the 50-300 m depth range, encompassing most of the main basin of the Strait, with the majority of the substrate soft sediments (see Figs. 2, 3). Only 18% of the subtidal area is >300 m deep and the majority of these areas are in the mainland fjords (Levings et al., 1983).

Zacharias et al. (1998a) used the BC Physical Shorezone Mapping System (Howes et al., 1993) as the basis of an analysis that provides an estimate of the total shoreline length of the SoG, including fjords (4107 km). The SoG's intertidal length is estimated to be composed of 26% rocky cliffs, 16% rock with gravel beach, 11% sand/gravel flats, 9.5% rock with sand/gravel beach and an additional 10 representative types each composing ≤7% of the shoreline; flats are those areas with slopes <5°, while beaches have slopes from 5°-20° or higher (Zacharias et al.

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1998b). The same authors estimate that the intertidal area of the SoG consists of 34% estuary wetland, 17% sand/gravel flat, 9% sand/gravel beach and an additional 11 types, each composing ≤6% of the intertidal area.

A review of marine ecosystem, or habitat, classification systems available for the SoG benthos, from the intertidal to the deep subtidal areas, is provided by Watson (1998). One of these, the British Columbia Marine Ecosystem Classification (BCMEC) system, was first developed in 1995 (Zacharias et al., 1998b, http://ilmbwww.gov.bc.ca/ cis/coastal/bcmec/index.html). BCMEC uses a tiered hierarchical system to define ecological boundaries for planning and administrative purposes (Howes et al., 1996). There are 12 ecosections in British Columbia, based on differences in ocean circulation, mixing, salinity, temperature, primary and total productivity, continental slope and shelf influence and freshwater influence (Harper et al., 1993a, b; Howes et al., 1996; Zacharias et al., 1998a). The SoG represents one ecosection, which is divided into smaller ecounits (ecological regions) based on a combination of five physical characters: wave exposure, depth, subsurface relief, current regime, and substrate type (Table 3– Wainwright et al., 1995; Howes et al., 1996; Zacharias et al., 1998a). Salinity and temperature data were later incorporated at the ecounit level into the SoG ecosection (Zacharias and Howes, 1998), as were stratification and slope (http://ilmbwww.gov.bc.ca/cis/coastal/bcmec/index.html). Depth, current and relief data used to develop BCMEC came from Canadian Hydrographic Service charts (depth, current, relief) (Lamb and Edgell, 1986; Wainwright et al., 1995), models (exposure) (Harper, 1995), and Geological Survey of Canada mapping of benthic sediments (substrate) (see Zacharias and Howes, 1998 for more detail) with intermittent ground-truthing (Howes et al., 1994; http://ilmbwww.gov.bc.ca/risc/). Fig. 2 illustrates the coarse resolution

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classification of the SoG, based on the system described above and using much of the collected data from the Provincial Physical Shore Zone Mapping System (Howes et al., 1994).

The subtidal components of the ecounits (Fig. 2) are based on extrapolation from data on the intertidal to shallow subtidal zones (≤20 m). This method produces a simplistic rendering of substrate types; the soft substrate areas are typically much more of a mosaic, frequently with mixtures of mud and sand, than are depicted, for example, in Fig. 2. This simple scheme is not designed, therefore, to capture the complexity of substrate types, but rather to provide a general perspective. Much more accurate and detailed information on subtidal slope, topography and substrate diversity is available from multibeam data (Fig. 3), as well as from collated sediment core and grab samples from a variety of sources (see Fig. 4). For example, the multibeam data show the deep subtidal reefs which have been found, using video transects, to be relic (or living) sponge and coral reefs (Conway et al., 2007; Cook, in press). Similarly, multibeam data have shown the complex delta structure and sedimentation around the mouth of the Fraser River and the southern portion of the Strait (Hill et al. in press). Although, the multibeam data is not useful at shallower depths (<30 m) (see Fig. 3), in combination with the physical and biological shore zone data (Howes et al., 1994; Frith et al., 1994), it provides a fairly comprehensive and reliable overview of the full range of benthic habitat depths in the SoG (Fig. 4) (see Burd et al, in press; Cook et al., in press; Hill et al., in press; Macdonald et al., in press).

Figure 4 shows a plot of sediment percent fines (silt+clay <63 µm particle size) to illustrate sediment types in the SoG. A more detailed map of the near-shore sediment types around the Fraser River delta north to Burrard Inlet is shown in Hart et al. (1998). Note that the greater

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detail in Fig. 4 can aid in identifying localized "anomalies". For example, coarse sand is evident around the Iona outfall (source unclear), at sand heads just south of the mouth of Burrard Inlet, and at the mouth of the south arm of the Fraser River.

1.3.2. Sedimentary Processes

The sedimentary regime for the SoG is extremely complex, particularly around the Fraser River delta and associated areas receiving maximum deposition from the river (see Hart et al., 1998). Sedimentary features of this area are described in detail by Hill et al. (in press). Sedimentation rates, organic and inorganic fluxes for the Strait are described in more detail in Burd et al. (in press). For the sake of simplicity, this section on sedimentary processes divides the SoG into two equal regions north and south of the deepest part of the main basin (~400 m) which is located just south of Texada Island. North of this dividing line (which includes the northern basin regime; Section 1.2), the basin rapidly becomes narrower and much shallower (<200 m) creating a barrier to bottom-transported particulate material from the Fraser River (Johannessen et al., 2005b). Sediment characteristics north of Texada Island suggest that Fraser River material does not contribute to particulate deposition, and that natural sedimentation and organic flux, mainly from marine detritus, are much lower than in the southern half of the basin (Burd et al., in press).

In contrast to the northern half of the basin, the southern half of the basin (which includes the central and southern oceanographic regimes; Section 1.2) receives markedly higher sedimentation (organic and inorganic) (see Macdonald and Crecelius, 1994 for literature review) which is from the Fraser River (Burd et al., in press). This higher sedimentation is related to heavier material deposited primarily at the mouth of the river (up to 10 cm/yr–Hart et al., 1998)

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and transported along the bottom northward along the bank straddling the Fraser River mouths, as well as down the slopes to deeper areas (McClaren and Ren, 1995; Hodgins and Hodgins, 2000). As one progresses northward from the river mouth, sediments become progressively finer (see Fig. 4), and show characteristics of declining proportions of Fraser River deposits (Burd et al., in press).

However, the high sedimentation rates to the south of the Fraser River are also related to particulate deposition from the Fraser River plume during freshet. The dispersion patterns of the Fraser River plume, which can extend 2-10 m down from the sea surface during freshet (Thomson, 1981), are aerially visible during the summer months and have been tracked in detail with satellite imagery (Fig. 5). South of the Fraser River, sedimentation may also be related to upwelled fine sands (glacial material) from the southern Gulf Islands (Johannessen et al., 2006). This creates a patchy mosaic of mixed sand and silt substrates in the southernmost portion of the southern half of the Strait (Fig. 4). The sediments of the deep southern portion of the basin that are most subject to plume deposition are somewhat sandy, but finer in texture than those along the slope and bank on the east side of the SOG which receive the coarser, bottom-transported materials from the Fraser River. Therefore, it can safely be said that the southern and northern halves of the SoG constitute very different sedimentary regimes (see also Johannessen et al., 2003).

Boundary areas of high primary production occur in areas of turbulent mixing in the vicinity of the north and south island chains which constrict the entrances to the SoG (Parsons et al., 1981). However, the constrictions at both the north and south end of the SoG result in very little

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exchange of particulates and, therefore, of contaminants which are bound to particulates, between the Strait and surrounding waters (Macdonald and Crecelius, 1994, Johannessen et al., 2003). In contrast, however, water-soluble contaminants can spread broadly outside the confines of the Strait (Macdonald and Crecelius, 1994).

Sedimentation in the fjords of the SoG is largely isolated from the effects of the Fraser River. Within the fjords, sedimenting material may arise from freshwater sources, delta slope failures, marine detritus and/or terrigenous erosion of the steep surrounding rock cliffs. The mainland fjords are bounded by the coast mountain range, so that much of the runoff in stream sources is of glacial origin (www.pac.dfo-mpo.gc.ca/SCI/osap/projects/bcinlets). Material sedimenting within fjords is typically fine and is trapped within the fjords' basins by the shallow sills at the mouth (Thomson, 1981).

Turbidity in BCs mainland fjords increases as the degree of freshwater and glacial runoff increases. Turbidity currents originating with delta slope failures at the heads of inlets are likely responsible for the bottom water turbidity in some inlets (Pickard and Giovando, 1960; Bornhold et al., 1994). In Knight Inlet, extremely high turbidity and seasonal vertical flux of glacial silt from the two rivers that discharge into the head of the Inlet result in suspended matter concentrations >100 mg/L and a delta slope sedimentation rate of 4 kg/m^2/d in summer. As commonly occurs in the mainland fjords, vertical flux and turbidity in Knight Inlet decrease progressively down the Inlet (Farrow et al., 1983). In contrast, Jervis Inlet has very low freshwater input and, thus, has remarkably clear water throughout the Inlet and at all depths

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(www.pac.dfo-mpo.gc.ca/SCI/osap/projects/bcinlets/Jervis_Inlet_e.htm; observations from the submersible PICES IV, Burd, unpublished data).

Sedimentation rates for the main basin of Howe Sound have been estimated at 0.4 cm/yr (Hickin, 1989) and for the area just outside the Sound's sill at 0.4 to 0.78 cm/yr (Johannessen et al., 2003). Howe Sound has a relatively high freshwater input (Section 1.2) which results in high levels of glacial, suspended particulates near the estuaries. Sediment types and probable transport patterns in Burrard Inlet are complex but have been described by McLaren et al. (1993) and McLaren (1994). Constrictions within the Inlet and high currents create zones of coarse sand grading to hard substrate beds (Thomson, 1981), and tend to maintain particulates in suspension throughout the Inlet. Dredging is required to maintain the channel at First Narrows (near the Lions Gate outfall), suggesting net deposition. Similarly, high net sedimentation rates (1 cm/yr) in Port Moody Arm necessitate continued dredging of the deep-sea berths (Levings and Samis, 2001).

In Saanich Inlet, the majority of the shoreline consists of steep, rocky cliff walls with embayments consisting of typical mud/sand flats with some eelgrass beds. The BC Provincial synthesis report for the Saanich Inlet Study initiated in 1994 concisely summarizes the benthic habitats and sediment types for different sections of Saanich Inlet (BC Ministry of Environment Lands and Parks, 1996). The information is limited primarily to habitats at depths $\leq$50 m adjacent to the shore; due to the hypoxic/anoxic nature of the deeper basin areas >50 m, biotic production is limited considerably.

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2. Benthic Habitats and Invertebrate Communities

Although this review is concerned primarily with subtidal habitats in the SoG, Section 2.1 provides a brief overview of pertinent studies on the intertidal invertebrate communities and habitats of the SoG; descriptions of the intertidal invertebrate biota are not included *per se* but can be found in the references cited. For example, Watson (1998) provides a list, and a short review, of studies on intertidal benthic community structure studies that were carried out in the SoG prior to 1997. Major sources of data on the intertidal zone in the SoG, specifically mapping programs and surveys associated with commercially important species, are reviewed in Sections 2.1.2 and 2.1.3, respectively. The bio-physical structure of the intertidal zone can strongly influence the habitat type and biota of the subtidal region and, therefore, aids in providing context for understanding subtidal habitats (Section 2.2).

2.1. Intertidal Zone

2.1.1. Intertidal Habitats

In contrast to subtidal habitats, which tend to be more physically predictable, intertidal habitats are influenced by greater variability in physical factors (e.g. waves, tidal currents, erosion, slope, light, air exposure, temperature, salinity, sediment stability). Factors that also affect subtidal habitats, such as tidal currents, can also affect intertidal areas; for example biodiversity tends to be enhanced in intertidal areas with fast currents (Levings and Thom, 1994). The influence of these factors, as well as biological factors, can lead to spatial heterogeneity of intertidal assemblages in what appear to be similar habitats (Dayton, 1971; Denny et al., 1985; Maurer and

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Aprill, 2007). Section 1.3 describes the estimated proportions of the intertidal zone of the SoG that are made up of the different habitat types described below.

Levings and Jamieson (2001) assessed the fish habitat significance of the marine riparian habitat in the SoG. The marine riparian area is defined, by the authors, as the ecotone where aquatic habitat at higher tides merges into terrestrial habitat (i.e. the supralittoral). Levings et al. (1983) reviewed intertidal benthic communities in the SoG in relation to habitat type, specifically sand beaches, rocky shores, mud flats and vegetated areas. The authors provide a list of invertebrate studies conducted in each habitat type prior to 1982. Several studies on sand beaches, with many focusing on Boundary Bay, report on a range of invertebrates from macrofauna to meiofauna (Kellerhals and Murray, 1969; Harrison, 1981; Smith, 1981; Swinbanks and Murray, 1981). The most extensive mudflats in the SoG, and those most heavily researched in terms of invertebrates, are in the Fraser River estuary (see Levings et al., 1983) but research has also been carried out on the mud flat invertebrate communities of the Squamish Estuary (Levings, 1980b) and Vancouver Harbour (Levings and McDaniel, 1974). In the SoG, there is considerable variation in the slope and geology of the rocky shores, with corresponding biological changes (Bousfield, 1957; Levings et al., 1983). Faunal composition in this intertidal habitat type is thought to be influenced predominantly by these geological factors, in addition to water characteristics, wave energy and biological interactions (Levings et al., 1983). In their review of research on invertebrate communities in vegetated intertidal areas, Levings et al. (1983) demonstrate the importance of algae and eelgrass in structuring these communities.

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The importance of substrate type and vertical zonation on intertidal community composition is emphasized in most studies in the SoG (c.f. Stephenson and Stephenson, 1961a, b; 1972). For example, Burd et al. (1987) concluded that beach assemblages in Boundary Bay, BC are strongly controlled by sediment grain size. Early synoptic helicopter surveys of rocky shorelines in the strait are described in Ellis (1966), and the concept of vertical zonation and succession developed by Stephenson and Stephenson (1972) in the Strait has also been applied locations outside the SoG in BC (Ellis, 2002, 2003). Rock and gravel habitats are crucial for shellfish species, especially the recreational and commercially harvested bivalves (Levings and Thom, 1994). Larval settlement of Dungeness crabs (*Cancer productus*), as well as that of Manila clams (*Venerupis philippinarum*), tends to be higher in areas of shell hash, gravel or eelgrass (Thompson and Cooke, 1991; Dumbauld et al., 1993; Levings and Thom, 1994).

Other sources of information on intertidal restoration, conservation and mapping projects in the SoG include the BC Community Mapping Network (http://www.shim.bc.ca/) and the BC Coastal Eelgrass Stewardship Project (http://www. stewardshipcentre.bc.ca/ eelgrass/eelgrassfinalreport12_04.pdf). While invertebrate communities in eelgrass beds in the SoG have not been studied extensively, there is some evidence that these communities are biotically more diverse and structurally different than those in nearby bare sediments (Levings and Coustalin, 1975; Sibert, 1979; Burd et al. 1987; Seacology et al., 2001). The roots and rhizomes of eelgrass and the tubes of infaunal invertebrates reduce the mobility of a variety of burrowing species, including polychaetes, bivalves, crustaceans, and some echinoderms (Brenchley, 1982). Not only is burrowing time increased but hard bodied taxa, in particular, are restricted by the biogenic structures (Brenchley, 1982). In addition, eelgrass beds are known to

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provide protection from predators (Heck et al., 1989) and to encourage the settlement of fine, suspended particulate material, a potential factor in the noted differences in invertebrate community composition (Fonseca and Fisher, 1986).

Considerable baseline environmental information on the intertidal zone of Saanich Inlet was generated as a result of two proposed foreshore developments: a ferrochromium production facility in the 1980s (see Rescan Environmental Services,1988) and, a large-scale residential development at the site of the defunct cement plant at Bamberton (Williams, G.L. & Associates Ltd., 1991; Madrone Consulting Ltd., 1993). Neither of the proposed developments came to fruition, however. An extensive, and more recent, database is available from the sanitary surveys of clam beaches in Saanich Inlet (see Walker, 1995) and from eelgrass restoration projects in Todd Inlet (BC Coastal Eelgrass Stewardship project; http://www.stewardshipcentre.bc.ca/eelgrass/eelgrassfinalreport12_04.pdf). Similarly, the Saanich Inlet Seagrass Survey studied 67 locations (40.9 hectares total area) surveying intertidal and shallow subtidal areas; eelgrass was limited to three areas with soft bottom substrates (http://www.env.gov.bc.ca/wat/wq/saanich/siscr.html). There is also a wealth of uncollated information on the foreshore biota of Saanich Inlet from the local shore-keepers surveys (see Section 2.1.2), as well as unpublished data collected by W. Austin (Khoyatan Marine Laboratory, Sidney, BC).

At Boatswain Bank, just north of the Saanich Inlet sill, recent intertidal transect surveys were done as part of the baseline assessment for a proposed landfall site for the GSX pipeline (Seacology et al., 2001). This is an area of extensive intertidal eelgrass beds, as well as green algae (e.g. *Ulva/Enteromorpha*). Such habitats are considered to be important nursery and

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feeding grounds for juvenile fish and were meant to be avoided by the pipeline drilling rig. Although the pipeline project did not go forward, the report contains detailed data listing algae and invertebrates that are commonly associated with sheltered, near shore habitats in southern BC fjords. The authors describe this ecotype as a typical south-coast, shallow, sloping beach with mixed cobble/sand/ gravel substrate (Seacology et al., 2001).

The intertidal wetlands of the Fraser River estuary cover an estimated 17,000 hectares (http://www.env.gov.bc.ca/cdc/) and are also one of the most biologically productive systems in Canada (Levings et al., 1983; Kennett and McPhee, 1988; Harrison et al., 1999). Estimated productivity (based on biomass) for the 14,000 hectares of Sturgeon and Roberts Bank, including the main mud flats on the outer shores of Lulu Island totals 1440.6 kcal/m^2, broken down into vascular plants (eelgrass) (1320 kcal/m^2), microbenthic algae (diatoms) (65 kcal/m^2), benthic organisms (invertebrates) (40 kcal/m^2), phytoplankton (in water) (15 kcal/m^2) and zooplankton plus epifaunal invertebrates (0.6 kcal/m^2) (Levings, unpublished data). Macroalgae such as *Ulva/Enteromorpha* are not included in these estimates (Levings, unpublished data) but are occasionally present (Harrison et al., 1999). Plants clearly make up the greatest bulk of living material on the mud flats, by far, and likely provide critical habitat and/or food resources for the benthic invertebrate fauna. The diverse invertebrate fauna are described in Otte and Levings (1975). Primary benthic production and nutrient dynamics of the delta, as well as the foreshore area of Boundary Bay at the Canada/US Border (i.e. outside the influence from the Fraser River), were recently reviewed by Harrison et al. (1999).

All the other major estuaries in the SoG are subject to various conservation and restoration programs, for which information is available from a variety of sources. For example, research on

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the benthos of the Squamish River estuary was reviewed by Hoos and Vold (1975) and Levings et al. (1983), with an inventory of research efforts in the estuary basin provided by Hickin (1992). Research in the Nanaimo River estuary includes a study on the intertidal hyperbenthic populations (Sibert, 1981) and the relationship between meiofaunal abundance and intertidal log storage (Sibert et al., 1979). The Nanaimo and nearby Gulf Island marine shorezone areas were also the focus of rocky shoreline zonation studies by Stephenson and Stephenson (1961a, b; 1972). Reports on the SoG estuaries can also be found on websites, such as that of BC Hydro (http://www.bchydro.com/bcrp/reports/lower_mainland.html).

2.1.2. Shore Zone Mapping Programs

The Provincial Biological Shore Zone Mapping (and database) System (Frith et al., 1994) for British Columbia was designed to integrate with the Physical Shore Zone mapping (Howes et al., 1994; see Section 1.3) and is based on taxonomic groupings. The boundaries for units and components in the physical system, based on geomorphological parameters, are used to define boundaries for species assemblages (bands) in the biological system. A hierarchical coding system for biota is included and is based on taxonomic groupings. Components are sub-divided into across- shore areas of common species assemblages termed bands. Bands are defined by the dominant cover species and the colour and texture of that band visible from aerial videography, photography, or from ground surveys (Frith et al., 1994). Maps on a fine scale resolution can be attained at http://ilmbwww.gov.bc.ca/. Publications describing the development of this system, modeled characterization of intertidal communities and regional diversity are cited in Zacharias et al. (1998a, b, 1999), and Zacharias and Roff (2001).

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The Canadian Department of Fisheries and Oceans began the Shorekeepers' program for monitoring the intertidal zones of the British Columbia coast in 1996 in response to need for a new data acquisition program. The program, aimed at involving coastal communities and fostering stewardship of the coastal zone, was designed for the monitoring of intertidal habitat by non-professionals. Full details including survey design, field sampling, data acquisition, etc., can be found in Jamieson et al. (1999). Data from surveys conducted between 1996 and 2005 are accessible online (http://www.shim.bc.ca/atlases/sk/ main.htm). Although the design and limitations of survey methods for this program tend to produce a bias towards larger macrofauna, the resulting data set is cumulative and relatively large, which allows comparison of the biomass-dominant fauna to the physical characteristics used in the BC Shore Zone Mapping System. The Shorekeepers' program (Fig. 6) provides a refinement to the habitat classification of the BC system, including not only substrate type but also dominant algal coverage.

2.1.3 Surveys and Studies Associated with Commercially Important Invertebrates

The BC Shore Zone Mapping Program is also used to assess suitable habitat for invertebrate taxa with commercial or recreational fishery value. For example, based on species-specific substrate and habitat preferences, the relative suitability/rating for the success of Pacific oyster viability at beach locations in SoG can be mapped (Fig. 7). Manila clam suitability shows a very similar distribution (Fig. 7). The areas of "good" and "medium" viability correspond to sand and gravel platforms and sometimes the presence of eelgrass (Fig. 7) (http://ilmbwww.gov.bc.ca/).

The BC Clam Atlas was developed as a means of mapping commercial intertidal clam beaches (Manila, Littleneck and Butter) on the BC coast. The maps, area calculations and historical

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landings for the SoG area were published by Harbo et al. (1997), and the maps are presently online (http://www-heb.pac.dfo-mpo.gc.ca/maps/maps-data_e.htm). Information on stocks of these and other clams can also be accessed using the Canadian Department of Fisheries and Oceans Stock Status Reports and the Fisheries Management Plans for each species. Geoducks prefer to burrow in sand, silt and gravel from the intertidal to a depth of 110 m (Canadian Department of Fisheries and Oceans, 2000). Landings in the SoG are minor (less than 1/3 of the BC total) and most are collected subtidally by divers. Of the three typical intertidal species, Manila clams are the species harvested primarily from the SoG (Canadian Department of Fisheries and Oceans, 1999a, b; 2007). The Fisheries Management Plan for Intertidal Clams suggests that, presently, stocks are healthy but that the commercial trend is toward reduced landings as a result of reduction in overall effort, lower prices, and increasing alienation of beach space for shellfish aquaculture tenures.

2.2. Subtidal Zone

Levings et al. (1983) reviewed the available sources of subtidal benthic biotic data for the SoG up to that time. Examples of several large, unanalyzed data sources noted in that review include Ellis (1967a, b, 1968a, b, c), who provided quantitative data (including abundance of "apparent" species) resulting from comprehensive surveys of the subtidal fauna and sediments from a wide variety of geographic locations with the SoG. These studies employed similar methodologies (grab samples) to those used in more recent, similar studies (see Levings et al., 1983; Burd, 1992; Burd, 2006). Bernard (1978) reported the results of an extensive subtidal bottom survey of invertebrate fauna from the SoG. The author described, but did not enumerate, the dominant organisms captured primarily by trawling and divided the sampled

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areas according to depth range and substrate type. Although some grab sampling was carried out at key locations, the fauna included in Bernard (1978) are primarily epibenthic.

This section is based primarily on background conditions where anthropogenic impacts are expected to be absent or limited. Descriptions of subtidal biotic assemblages based on recent studies are separated by depth range and substrate type in a manner similar to Bernard (1978) but with two notable differences. First, four substrate types (mud/silt, sand, gravel and rock/cobbles) are used in Bernard (1978) while here we employ the following five substrate types: mud, silt/sand, sand, coarse sand/gravel/cobbles and rock (consolidated). Given that trawling was the main sampling method used in Bernard (1978), it is assumed that the rock substrate in rock/cobbles is not consolidated; therefore, the gravel and rock/cobbles substrates of Bernard (1978) are considered equivalent to our coarse sand/gravel/cobbles substrate. Inherent in these, and similar habitat classification systems, is that mixed habitats will have overlapping biotic community types. Second, whereas Bernard (1978) described biota from 20-50 m, and 50-100 m (primarily for logistical reasons related to towed sampling patterns), biota and available information for the SoG are reviewed herein for 3 depth ranges (see below: 0-30 m, 30-100 m, >100 m) based on evident biotic shifts noted at these approximate depths from the literature reviewed herein (see Burd, 2003a). An example of such a depth factor can be seen in Palsson et al. (2003), who state that in the fully surveyed Washington State side of the BC/Washington transboundary bottom trawl survey of 2001, 60% of the invertebrate biomass was found in the 5-20 fathom (approximately 10-37m) depth range. Although this depth range was not surveyed on the BC side of the SoG, invertebrate biomass declined dramatically with depth in the deeper sampling strata.

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The depth ranges are defined as follows:

A. 0-30 m corresponds, approximately, to the euphotic zone (depths within which light penetrates), although the depth of this zone varies considerably along the BC coast in relation to exposure and water clarity. 0 m depth is considered to be mean low tide, so that habitats within this depth range are subtidal;

B. 30-100 m encompasses the zone which, generally, has adequate water oxygenation due to influence of wind and tidal currents and which includes subtidal organisms and no primary producers. In any one location, the consistency of benthic communities in this depth range will depend on depth-related shifts in habitat type, physical features and hydrographic processes. Many of the major taxa, however, have habitat depth ranges which span 30-100 m;

C. >100 m encompasses habitats which experience a progressive decline in organic input and bottom currents, leading to considerable change in the benthic communities. In near-shore areas, these depths often occur at the bottom of basins (e.g. fjords) or the foot of coastal slope areas (SoG).

Because the complete particle size distribution (including an assessment of flocculent material) provides the most thorough information about depositional history, it is recognized that the following five substrate types are simplistic (Burd 2003a). In addition, many habitats, particularly near shore, are a heterogeneous mix of different substrate types over relatively small areas. The 5 substrate types, and general features of these substrates regardless of depth, are summarized below.

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1. **Mud bottoms (>95% silt/clay)** typically occur in low energy areas and are sticky and tightly packed; mean sediment grain size is <0.06 mm.
2. **Silt/Sand** substrates are a mixture of these two sediment types. The mean sediment grain size for this substrate type ranges from 0.04 to 0.5 mm.
3. **Sand (>90% sand)** substrates are typical of areas with moderate to high bottom currents and/or wave action and exposure, which prevent deposition of finer, marine deposits. Sediment grain size ranges from 0.5 mm to 2 mm.
4. **Coarse sand, gravel or fine cobble** sediments have a grain size from 2 mm to 26 cm. These substrates are less mobile than the previous substrate type, due to the size and weight of the particles, and are mobile only in high energy habitats.
5. **Rocky** substrates are composed of large cobble, boulders or bedrock and include reefs and outcroppings, rocky shorelines and fjord walls.

The above 5 substrate types are discussed in more detail below, citing research from both the SoG and similar environments elsewhere. These more detailed descriptions are relevant to understanding the diversity of subtidal habitats in the SoG. These depth- and substrate-specific habitats are described, including biotic structure, for the SoG using information gathered from a variety of data sources including unpublished remote sampling, submersible and ROV work, collections of data in unpublished data reports. Hence, these generic descriptions of the SoG subtidal habitats are synthesized and, in some cases, extrapolated from a variety of sources and do not lend themselves to specific citations. However, specific type examples from the SoG are provided for each depth- and substrate-specific habitat, including benthic invertebrate community data, when available.

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807 **2.2.1 Mud (silt/clay) Habitats**

808

809 The finest substrate habitats in the SoG are found typically in low energy areas. Although bottom
810 turbidity is unlikely due to storm, wave or current exposure in these low energy environments, it
811 can be caused by physical disturbance such as bioturbation and anthropogenic mechanisms. The
812 fine, often flocculent bottom material may take some time to settle once it is suspended via
813 bioturbation (c.f. Orvain et al., 2003). This is likely the case at fish farms, for example, where
814 organic ooze under the nets is sometimes resuspended by falling debris (e.g. sloughed material)
815 from the overlying nets (Stucchi et al., 2005). However, a distinction should be made between
816 turbidity resulting from static resuspension, due to physical disturbance in mud substrates, and
817 turbidity due to mobile suspended solids resulting from up-stream slope failures in estuaries (c.f.
818 Prior et al., 1987). In the first case, and for most mud sediments, typical bottom disturbances
819 result in low net sediment transport. However, for up-slope failures or slumps, there likely will
820 be considerable transport and bottom turbidity can persist for some time (Prior et al., 1987;
821 Bornhold et al., 1994).

822

823 Sediment organic content can be highly variable in silt/clay sediments, depending not only on
824 organic deposition but also on inorganic deposition (see Burd et al., in press). For example, high
825 glacial silt deposition in more northerly mainland fjords tends to be low in organic content (c.f.
826 Farrow et al., 1983). The ratio of organic to inorganic deposition can be related to water depth
827 since, with increasing depth, inorganic (land-based) deposition tends to decrease while the
828 deposited material becomes increasingly dominated by marine detritus (c.f. Rhoads and Young,

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1970). In the southern SoG (i.e. south of Texada Island), deposition to mud substrates is dominated by particulates from the Fraser River (Thomson, 1981; Harrison et al., 1983; LeBlonde, 1983; Johannessen et al., 2003). This deposition produces organic carbon levels in surface sediments averaging around 1% near shore in the most southerly portion of the main basin and around 2% in the deeper basin sediments, closer to Texada Island (Burd et al., in press). This observed trend is due to declining riverine deposits and increasing marine deposition (Johannessen et al., 2005b). In the northern SoG, the basin sediments show unusually high %TOC (3-6%) but the overall flux of organic material, and total sediment, to the benthos is low (Johannessen et al., 2003; Burd et al., in press). Stable isotope data and biological samples also suggest that organic material in sediments in the northern SoG is not particularly labile (Burd et al., in press; Macdonald et al., in press).

Not surprisingly, mud substrates are usually suboxic or anoxic, although %TOC varies (~1-7%) depending on the levels of inorganic input, and hydrogen sulphides or other metabolic byproducts may build up depending on redox levels and labile organic input. In shallow mud (silt/clay) substrates, sulfate reduction tends to be linked to a significant proportion (>50%) of carbon oxidation, whereas in deeper mud sediments (continental shelf) the breakdown of organic material is relatively evenly distributed between aerobic and anaerobic (sulfate reduction) processes (Kristensen and Kostka, 2005). The density of infaunal burrows, however, can have a profound dampening effect on anaerobic metabolism as a result of the increased oxygen supply to subsurface sediment layers. The predominant type of burrowing is related to trophic mode (Nickel and Atkinson, 1995), as well as sediment texture and geochemistry. Fine sediments tend

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to be dominated by surface deposit feeders or above-surface filter feeders (Kristensen and Kostka, 2005), rather than sub-surface deposit feeders.

Extensive surface bioturbation without the binding influence of intact burrows can destabilize fine surface sediments by producing a surface ("fluff") layer which is readily re-suspended (c.f. Rhoads and Young, 1970; Orvain et al., 2003). Rhoads and Young (1970) even suggest that surface fluff layers tend to prevent suspension feeding due to the clogging of feeding apparatus and the inhibition of larval settlement. The authors use this suggestion to explain the distinct dichotomy in dominant feeding types: deposit-feeders in soft, fine sediments versus suspension feeders in sandier, or firmer, mud sediments. Following this line of reasoning, an assessment of the feeding guilds in sediments could provide some insight into the sediment texture and porosity, as well as near-bottom turbidity.

The fine-grained particles of mud substrates tend to contain considerable organic particulate material in various forms, thereby providing a good substrate for bacterial and/or algal production (Kristensen, 1988). Key general biotic features of mud bottoms include extensive bacterial or algal mats or shallower near-surface invertebrate burrows that provide sediment surface cohesion in shallow depths, or from invertebrate burrows. Microbial activity, which breaks down organic material in marine sediments (Kristensen and Kostka, 2005), can be stimulated by the presence of surface mucous layers from meiofauna (see Probert, 1984). The stimulation of both microbial and meiofaunal activity creates a rich organic food layer for macrofaunal deposit feeders (Hoskins et al., 2003, Hannides et al., 2005; for review see Kristensen and Kostka, 2005). In addition, mucous layers from intertidal mudflat diatoms,

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bacteria and mucous-lined burrows can also help to bind the sediment surface (c.f. Decho, 2000; de Brouwer et al., 2005). Mucous burrows are often impermeable to dissolved organic material and redox chemicals in order to protect the animal from harsh chemical environments (c.f. Hannides et al., 2005; Kristensen and Kostka, 2005). However, depending on their structure, these burrows do provide a pathway for exchange of overlying water with deeper sediments, thus preventing the buildup of potentially inhibitory metabolic byproducts (see Zorn et al., 2006). However, the importance of both bacterial and diatomaceous mucous layers in sediments declines in importance with increasing depth from the intertidal zone to the bottom of the euphotic zone (Ziervogel and Forster, 2006).

Where oxic sediments are present in these habitats, macrofauna are primarily deposit feeding shallow burrowers, such as polychaetes and bivalves, and predators such as various flatfish and crabs from surrounding rocky areas. Megafauna typically include a variety of echinoderms such as mud stars and burrowing holothurians.

2.2.1.1 Shallow (0-30 m) mud

Mud substrates in the shallow subtidal tend to be protected from wave exposure and typically have low tidal currents. Bottom turbidity in these habitats is likely due to physical disruption from erosional events, delta slope failures or other unusual events. These habitats typically occur in low flow estuaries and at the base of low current rocky outcrops. Shallow mud habitats can be found in quiescent bays surrounded by rocky headlands, and in wave and current protected estuaries with either low freshwater flow or where there is heavy glacial silt in runoff (i.e. estuaries of mainland fjords; see Farrow et al., 1983).

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These are typically highly productive areas because they are within the euphotic zone, which allows primary production as well as bacterial production on and within the sediments. They are also common in coastal areas with physical developments that block or break up wave erosion (e.g. marinas, breakwaters, etc.). Surface shell debris can be common, attesting to the importance of bivalves in this food chain. Organic carbon flux to the sediments may be high and, hence, sediment %TOC may also be high depending on the level of inorganic input. (Boyd et al., 1998). If the input is primarily salt-marsh plant debris, however, the organic material may have low lability. Primary production in these habitats is primarily from benthic micro-algae and blue-green algae (refs). These sediments typically have a high level of bacteria, which can include sulphur-fixing species (refs).

Usually, these areas have oxygenated bottom water, with sufficient oxygen for shallow burrowers that are mostly deposit feeders (bivalves and polychaetes), epifauna (scavenging amphipods and bottom shrimp), surface grazers (gastropods) and predators (mud stars, brittle stars, heart urchins, echiurans, drills, fish) (Burd, 1992). In some habitats, mud-dwelling sea cucumbers such as Molpadia or *Chirodota* may be found if there is sufficient oxygen in surface sediments (Burd, 1992). Meiofauna, particularly nematodes, are important in these shallow subtidal mud habitats (see section 1.1).

Examples can be seen in areas such as Patricia Bay, Saanich Inlet, and around numerous estuarine bays in the Strait. Unfortunately, there are few published examples of shallow subtidal mud studies in the SoG. Burd (1992) and Boyd et al. (1998) described mud assemblages from

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shallow areas of the innermost part of Burrard Inlet (Port Moody Arm). These substrates had low invertebrate abundance and biomass compared with deeper, coarser substrate areas further out in the inlet, and were dominated by polychaetes, followed by bivalves and crustaceans. Faunal composition was distinct between Port Moody Arm and areas further out in the inlet (Burd, 1992) and in some areas with reducing sediments, dominated by the tolerant opportunistic polychaete *Capitella capitata* complex (Boyd et al., 1998), Considerable sediment chemical contamination and organic enrichment are evident in the Port Moody Arm area (see Burd, 1992; Boyd et al., 1998).

2.2.1.2 Mid-depth (30-100 m) mud

Mud substrates at 30-100 m depth are a common marginal habitat around the SoG, particularly on the eastern side, including Burrard Inlet, north along the coast, and in isolated bays with low bottom currents (Fig. 1). These fine-grained substrates are not found in areas exposed to sandy deposition from the southern Gulf Islands, the Fraser River discharge and other relatively large freshwater estuaries such as the Cowichan River (north of Saanich Inlet), and the Squamish River (Howe Sound). This type of habitat is commonly found inside the sill, or near the mouth of fjords, in areas with either limited, or absent, bottom currents and very low freshwater runoff. These habitats may also occur surrounded by, or at the base of, rocky outcrops or cliffs. Bernard (1978) lists the dominant invertebrate epibenthic megafauna (11 species) found in mud/silt habitats from 20-100 m depth at multiple locations within the SoG.

Because of the depth range, these habitats tend to have limited tidal influence and no wave influence. In addition, as the mud substrates are below the euphotic zone, the development of

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surface biofilms may be less extensive than in shallow subtidal mud habitats (c.f. Ziervogel and Forster, 2006). If the redox boundary occurs at the sediment surface, however, sulfide-fixing bacteria such as *Beggiatoa* spp. may produce mucous mats. For example, *Beggiatoa* spp. mats can be found between 65-100m depth in areas of Saanich Inlet (Burd, unpublished data; see >100 m anoxic basins, below).

An example of this type of habitat is bottom areas shallower than sill depth in Saanich Inlet, such as Patricia Bay (http://www.env.gov.bc.ca/wat/wq/saanich/siscr.html). Although there have been no studies focused on the benthic soft-bottom fauna in the mid-depth range of Saanich Inlet sediments, another example of this habitat type in the SoG, for which data are available, is outer Burrard Inlet. Sedimentation rates are low in this region (Johannessen et al., in press), although the complex hydrographic mixing results in high suspended particulates in the water column (as noted during reconnaissance ROV surveys – CORI, 2002) and sediment TOC levels between 1.5 and 2% (McPherson et al., 2006b). Although there are a variety of anthropogenic discharges and physical disturbances in the inlet (see Section 3), long-term monitoring for the outer inlet suggests that benthic infauna are not impoverished and are not dominated by opportunistic polychaetes (c.f. PICES, 2001; McPherson et al., 2006b). Fauna within the inlet are dominated by small burrowing bivalves, which constitute ~55-85% of the total abundance over a range of sediment enrichment conditions and which contribute the largest percentage of biomass of any major taxonomic group (McPherson et al., 2006b). Polychaetes constitute 10-40% of the total abundance and species numbers are within the ranges expected for this depth range in the SoG (Burd et al, in press). Ophiuroids are patchily abundant and both crustaceans and holothurians are rare in this inlet.

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Data are also available for shoreline areas just outside the north side of Burrard Inlet which fit this habitat type (McPherson et al., 2004a). Biotic samples taken from a similar depth to the outermost Burrard Inlet show similar species richness to the Burrard Inlet samples but somewhat lower abundance levels (McPherson et al., 2004 a, c). Fauna increase in abundance from outside the inlet to the innermost part of the outer basin (west of 1st Narrows) (Fig. 1), with bivalves showing the clearest abundance gradient (McPherson et al. 2004 a,c). Like Burrard Inlet, the area just outside the north side of the inlet experiences relatively low sedimentation rates compared to the rest of the southern SoG, as well as moderate %TOC in the sediments (~1.5%) Burd et al., in press; (Johannessen et al., in press).

Biotic and synoptic sediment geochemical and contaminant sampling data have been collected for parts of inner Burrard Inlet (past 1st Narrows), including the two inner arms (see Fig. 1) (Burd and Brinkhurst, 1990; Cross and Brinkhurst, 1991; Boyd et al. 1998; PICES, 2001; Je et al., 2003). In addition, samples from the outer inlet were collected by Ellis (1971). These studies suggest that faunal abundance and species richness decline along a gradient from 1st Narrows inward towards Port Moody Arm (Fig.1), where the heaviest organic enrichment and contamination is found. In Port Moody Arm, which has fine mud sediments with poor flushing, faunal abundance tended to be temporally variable relative to the rest of Burrard Inlet (Burd 1992; Boyd et al., 1998) but faunal biomass was consistently lower.

The spectrum of studies utilizing the same locations in Burrard Inlet but using different mesh sizes (0.3, 0.5 mm and 1 mm) for screening biotic samples, provides a unique opportunity to

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examine the difference in interpretation which is potentially possible for community structure based on methodology. Ignoring potential differences in quality control of sampling, increasing screen mesh size led to a decreasing proportion of juvenile (non-adult) forms at one outer harbour station (~ 50% to 10%) but no notable shift in species number. However, the proportion of abundance made up of bivalves shifted from ~35% to 55%, with a commensurate decrease in proportion of polychaetes. In addition, although usually ignored in benthic macro-infaunal studies, the proportion of nematodes collected decreases with increasing mesh size. Hence, the 1mm screen appears to eliminate most of the juvenile fauna, as well as a modest proportion of the smaller adult polychaetes and most of the "meiofauna" (primarily nematodes and harpacticoid copepods). The most dramatic change in metazoan size spectra, biota types and life history strategies appears to be found at about the 0.5 mm screen size, and the evolutionary drivers for the meiofaunal/macrofaunal dichotomy are discussed by Warwick et al. (2006). The various studies agree that polychaete dominance increased from the outer inlet towards the more eutrophic Port Moody Arm (Boyd et al., 1998; Burd and Brinkhurst, 1990; Je et al., 2003), with some examples of opportunistic enrichment of *Capitella capitata* complex (Burd and Brinkhurst, 1990; Je et al., 2003).

2.2.1.3 Deep (>100 m) mud

Deep water mud habitats are not subject to tidal or wave influences, usually have very low bottom currents and limited flushing of bottom water. The origin of organic material in these environments is primarily marine detritus or terrestrial erosion from cliffs in fjords. Bottom turbidity can occur as a result of turbidity flows from delta slope failures in fjords (Prior et al., 1987; Bornhold et al., 1994). In general, substrates get finer with increasing depth in coastal

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areas (Striplin, 1996; Llansó et al., 1998) because the input of coarser land-based erosional, riverine and current-transported material tends to decline with increasing depth. Organic carbon flux to these deep sediments is typically, although not always (Burd et al., in press), lower than in similar sediments in shallower areas, unless there is a specific source of organic input nearby (e.g. fish farms).

Areas with oxygenated, mud sediments are extensive throughout both the deep basin of the SoG and many of the fjords, and probably make up most of the subtidal bottom area of the SoG (Levings et al., 1983). Bottom water oxygen levels vary, depending on basin topography, but low bottom currents and shallow, isolating sills in fjords can result in significantly reduced bottom oxygen levels. Hence, there is limited oxygen replenishment to the sediments. These habitats are typical of the main basins of fjords and the deep basin of SoG. These sediments are dominated by near-surface, or epifaunal, deposit feeders and predators. Bivalves and ophiuroids are less abundant in these deep habitats than in shallower areas, while polychaetes, holothurians and echinoids increase in dominance (see Burd et al., in press). Bernard (1978) provides a list of the dominant (largely epibenthic) megafauna collected in trawl samples at locations throughout the SoG at depth ranges of 100-200 m, 200-300 m, and 300-400 m. Bernard's (1978) species list is the most diverse in all depth ranges for this substrate type, and includes bivalves, polychaetes, echinoderms and crustaceans.

Because organic carbon flux is low, faunal abundance and species richness is generally lower than in the mid-depth marginal SoG mud habitats discussed earlier. Llansó et al. (1998) describe biotic conditions in deep clay habitats >80 m in Puget Sound. They suggest that, on average,

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species richness and abundance was lowest in deep (>80 m) clay sediments of any soft substrate types in the sound or on the Washington shelf. Llansó et al. (1998), Burd and Brinkhurst (1992) and Burd (2003b) agree that several of the large, important bioturbators (the echinoderms *Molpadia intermedia* and *Brisaster latifrons)* seem to be primarily found in deep-water sediments, which in the fjords and main basin of the SoG are typically mud (silt/clay).

Some data on the benthic infaunal biota, collected using visual and remote sampling methods, are available for the fjords (Burd and Brinkhurst, 1992; Ellis, 1971; Levings, 1980a, b). Burd and Brinkhurst (1992) report infaunal abundances in silt sediments at depths of >100 m in of three of the SoG fjords: Bute, Toba and Jervis. Faunal abundance was low at all sampling stations in that study and was dominated by polychaetes; occasional high abundances of sipunculids were recorded but few echinoderms and virtually no crustaceans or bivalves were observed (Burd and Brinkhurst, 1992). Burd (1992) did a multivariate comparative assessment of biotic assemblages from a series of deep fjord samples along BCs mainland coast compared with other assemblages found throughout BC. One notable feature of BC's deep fjords is the relative uniformity of benthic assemblages in the deep mud benthos, compared to other coastal areas, in the absence of overwhelming physical drivers such as anoxia or hypoxia, heavy glacial deposition or freshwater runoff (c.f. Burd 1992).

Ellis (1971) described fauna from some grab samples taken in the deepest basin of Jervis Inlet on the mainland BC coast. They note that about 80% of biomass from that area was contributed by the echinoderm *Brisaster latifrons* and a surface tube-mat forming polychaete; approximately 10% of the total biomass was contributed by bivalves.

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A deep mud-bottom habitat in Knight Inlet (located immediately north of the SoG), described in Farrow et al. (1983), is a good example of a fjord with high loads of river-borne glacial silt. These loads of glacial silt add to the inorganic loading near the head of the inlet, while also introducing sufficient energy and flocculent material into the system to produce high turbidity and bottom resuspension or turbidity flows. This turbulent type of habitat is unsuitable for many soft-bottom species which may suffer from smothering (e.g. Holte and Gulliksen, 1998; Wlodarska-Kowalczuk et al., 2005). In Knight Inlet, BC, Farrow et al. (1983) found a down-inlet gradient of increasing diversity of large suspension-feeding organisms, and a change in epifauna from mobile shrimp and crabs at the turbid, high inorganic input head of the inlet, to burrowing shrimp in the middle inlet, to ophiuroids in the least turbid and least inorganic input areas of the lower inlet. Similar trends have been observed elsewhere; for example Wlodarska-Kowalczuk et al. (2005) describe the spatial gradient in sediment biota away from heavy glacial silt sedimentation towards the head of a European fjord as showing similar trends in faunal abundance and species richness as those found in organic enrichment gradients. Changes in species diversity and types of sponges related to water turbulence and sedimentation in an Irish sea lough were also noted by Bell and Barnes (2000a, b).

During the SoG Ambient Monitoring Program (Wright et al., in press), deep-water mud habitats were sampled at two stations. One station was within the deepest part of the SoG basin (388 m), just south of Texada Island (Fig. 1), and had moderate organic flux to sediments while the second station was north of the mid-basin sill near Texada Island (187 m) and was within the low organic flux regime in the northern SoG (see Burd et al., in press). In addition, the organic

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carbon at the shallower, more northern station was relatively refractory compared with the deeper, southerly station, and had a high clay component, with virtually no terrigenous or shell debris. The difference in these substrate conditions produced a striking difference in biota, which was much more abundant and diverse at the deeper, southerly station. However, similarities between the two stations include polychaete dominance, the lack of bivalves and crustaceans, and the presence of large burrowing holothurians. In fact, this latter group was responsible for the relatively high faunal biomass at the deeper, southerly station (Burd et al., in press).

Saanich Inlet, below sill depth (70 m) (Fig. 1), is an example of a deep anoxic basin. It experiences progressive hypoxia and anoxia from winter through summer. In the fall, upwelling within the SoG spills dense, oxygenated water over the sill and, sinking to the bottom, this water pushes the anoxic layer up to mid-water depths before the anoxic waters disperse (http://www.pac.dfo-mpo.gc.ca/sci/OSAP/projects/bcinlets/saanich_inlet_e.htm). Saanich Inlet has high organic carbon content in deep sediments (Bornhold, 1978) but a moderate C/N ratio (~6.8), suggesting that, historically, the origin of organic input has been largely marine. The high carbon content in Saanich Inlet deep sediments has been supported by more recent studies (Boatman and Murray, 1982; Tunnicliffe, 2000), however Tunnicliffe (2000) indicates that increasing terrestrial input over the past century has resulted in shifts in organic carbon content, and therefore, the C/N ratio. Organic carbon may build up in sediments because overlying water hypoxia and anoxia greatly slow the decomposition and consumption of this material by bacteria and invertebrates, respectively (Emerson and Hedges, 2003). Although the cliff fauna of Saanich Inlet have been studied, (Tunnicliffe, 1981; Burd and Brinkhurst, 1984), information on the infaunal benthos of the deep mud basin is lacking. However, because of the occasionally

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vertically mobile anoxic water layer in this inlet, along with observed mass mortalities of cliff fauna (Tunnicliffe, 1981; Burd and Brinkhurst, 1984), it has been assumed that soft-bottom areas influenced by long-term anoxia will be largely azoic.

At the sediment interface, where dissolved oxygen is minimal and sediments are anoxic, white mucous mats of *Beggiatoa* spp. and similar sulphur-fixing bacteria may form (Burd and Brinkhurst, 1984). In this oxycline, the sediments are devoid of any sign of bioturbation or evidence of infaunal or epifaunal life (Gucluer and Gross, 1964; Burd, unpublished data; PICES IV observations 1980-1983), with the following exceptions. A bentho-pelagic amphipod species (*Orchomene obtusus*) can tolerate anoxic conditions for extended periods of detrital scavenging, after which they migrate back up to oxygenated water periodically (De Robertis et al., 2001). The galatheid crab, *Munida quadrispina*, has been observed to frequent silty bottom areas where the mucous mats are present and near-bottom water oxygen levels are very low (Burd and Brinkhurst, 1984) and has been observed, *in situ* and in the laboratory, to feed opportunistically on sediment detritus and the aforementioned amphipods. The crabs have exceptional metabolic regulation under low oxygen conditions in the laboratory (Burd, 1985), along with significantly hypertrophied gill tissue in the deep areas of Saanich Inlet (Burd, 1988), compared with surrounding areas outside the inlet. In the deep, severely hypoxic to anoxic sediment areas, these are the only visually evident fauna although facultative anaerobic meiofauna (typically nematodes) may be present in sediments.

Like Saanich Inlet, Howe Sound on the mainland coast of BC has a shallow sill at the entrance and experiences hypoxic conditions in the deep basin for part of the year. Historical bottom

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trawl surveys in Howe Sound related to bottom hypoxia are described in Levings (1980a, b) and Levings et al. (1983). Survey data show that the relatively immobile invertebrates and a few slow-moving fish experienced mass mortalities during severe hypoxic periods; bottom fish catches declined, presumably due to migration to shallower, more oxic waters. The mobile epifauna appeared to return fairly rapidly following hypoxic periods, including the galatheid crabs also found in Saanich Inlet, and various shrimp species (Levings 1980a, b).

2.2.2 Silt/Sand Habitats

The presence of sand implies transport of inorganic material, from nearby glacial deposits or moderate to high input from freshwater sources nearby. Although variable spatially and temporally, these sediments are net depositional. In coastal areas with a source of relatively coarse, inorganic material from large riverine inputs, the sediments tend to be mixed. This type of habitat is common in marginal coastal areas in the southern SoG, particularly along the eastern margin of the southern Strait where the Fraser River discharges. For a description of sedimentary dynamics along the Fraser River delta, see Hill et al. (in press). Most notable about these sediments is the input of coarse material that increases mobility beyond that found in mud substrates. The delta sediments along the bank and slope where the Fraser River discharges into the SoG provide a good example of this mobility, as the sediments appear to be continuously transported to the north and downslope (McLaren and Ren, 1995; Hodgins and Hodgins, 2000). The importance of sediment mobility in determining the distribution and stability of coastal benthic infauna has been documented in Australia (Post et al., 2006), New Zealand (Hewitt et al., 1997; for a general review see Newell et al., 1998), and in laboratory experiments (Roegner et

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al., 1995; Dunn et al., 1999; Hunt and Mullineaux, 2002). Research in the northeast Pacific has focused on transport of sediment particle sized organisms such as foraminifera (Snyder et al., 1990).

In the sediments influenced by Fraser River deposits, the relatively high deposition of inorganic riverine material seems to limit the TOC levels to values <1.5% (McPherson et al., 2006a; Burd et al., in press). However, these TOC values are not indicative of the productivity of these sediments, which is more closely related to the input of organic material (see Burd et al., in press). Because of the inorganic input to these sediments, however, and their tendency to be less sticky and cohesive than mud, they are usually better oxygenated that marine muds. Surface mixing layer depths related to bioturbation in substrates affected by Fraser River discharge are estimated at between 7-10 cm deep (Johannessen et al., in press). These substrates tend to be located in moderate or variable current regimes and, because the sediments are easily re-mobilized, bottom turbidity may occur. These substrates are typically oxic but, if organic carbon loading is high, can be suboxic.

A wide range of habitat types, based on fine-scale structural features, can be found in these substrates, along with a mixture of biotic features of both mud and sand communities. Analyses of biotic data with an extensive geographic distribution within the SoG (Burd et al., in press), indicates that this silt/sand habitat along the Fraser River delta appears to have a high abundance of invertebrate fauna compared with the rest of the SoG. Biota are diverse in terms of species richness, type (polychaetes, bivalves, echinoderms, crustaceans and more) and size spectrum of organisms, as well as feeding types (mixed deposit and/or suspension feeders, scavengers and

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predators) (McPherson et al., 2006a). Using functional group categories for benthic fauna, Pearson and Rosenberg (1978) suggest that off-shore silt/sand habitats in temperate coastal areas tend to have the greatest diversity of functional groups in soft sediments.

2.2.2.1 Shallow (0-30 m) silt/sand

Shallow silt/sand habitats in the SoG are usually semi- protected in regard to wave exposure and tidal currents. Sediment is either fluvial in origin or from an along-shore source. Oxygen levels in bottom water are reasonable and natural sediments tend to have some oxygenation. In the SoG, eelgrass occurs in oxic sediments in areas with "clean" water and at depths usually <10 m. Both red and green macroalgae are associated with eelgrass beds, as a result of the low sediment mobility (eelgrass roots/rhizomes stabilize the sediments). In the shallow silt/sand habitats in the SoG, mobile macrofauna (e.g. sea stars and crabs) are abundant and, usually outside of the eelgrass beds, deep-burrowing large bivalves as well as burrowing anemones, agglutinated tube-building worms and tubicolous amphipods occur.

Bazan Bay on Vancouver Island, serves as an example of some of the more interesting features that may occur in these shallow silt/sand habitats. A mixed eelgrass, red and green filamentous algal community is evident to the 10 m depth (J. Harper, CORI, Sidney, BC, pers. comm.), along with patches of eelgrass that vary in density (see Bornhold and Harper, 2002). Eelgrass beds are typically considered to be important habitat and nursery areas for various species of fish and mobile, or epiphytic, macro-invertebrates (Goldstein et al., 1996; Heck et al., 2003; http://www.ecy.wa.gov/programs/sea/pugetsound/species/eelgrass.html)

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In deeper waters, but still within this habitat type, foliose red algae and other macroalgae are seasonally abundant, suggesting attachment in the relatively stable silt/sand substrates. Benthic invertebrate data from close proximity to an abandoned outfall pipe in Bazan Bay was collected (Glaholt et al., 2002) as part of the reconnaissance information related to the proposed SoG Crossing pipeline project. The study was designed to show the expected changes in biota related to the introduction of an artifical reef (a pipeline), into a shallow, silty sand habitat in the SoG. The faunal assemblage in these substrates is dominated, to an indeterminate water depth, by a dense sediment-surface mat of tube-dwelling amphipods, sponges and hydroids, with lesser dominance by polychaetes, followed by bivalves (Glaholt et al., 2002). The presence of these mats suggests a lack of bottom disturbance from excessive sedimentation, organic input or physical disruption. The presence of sponges and hydroids in the mats suggests a strong suspension feeding component within the community. The amphipod tubes produce a micro-heterogeneity of structure which benefits other species, such as the hydrozoans and a multitude of other amphipods and crustaceans. Faunal distributions were highly variable spatially, with isolated patches of anoxic sediments and higher silt content where drift algae had piled up on the quiescent down-current side of the Bazan Bay pipeline (Glaholt et al., 2002). Other infaunal organisms which may be common in shallow silt/fine sand habitats include relatively deep burrowing, large bivalves, burrowing anemones, and larger mobile predators and scavengers (e.g. mud stars, crabs, shrimp and nudibranchs).

Another example of a shallow mixed silt/sand habitat study is Boatswain Bank along the eastern coast of Vancouver Island just north of Saanich Inlet. A shallow subtidal study was done along an onshore/offshore transect at the proposed landfall for the SoG pipeline. The relevant habitat,

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macroalgae and surface megafauna are described based on diver surveys in Seacology et al. (2001). Megafauna included sea-pens, tubeworms, gastropods, hermit crabs, sand stars, and various fish. Beach seining in the same study showed a number of rock, kelp and helmet crabs. Concurrently, a study of the infauna (Burd and Glaholt, 2000) showed a diversity of polychaete, bivalve, crustacean and echinoderm fauna with numerous bryozoan and cnidarian colonies attached to fauna and macroalgae. The diversity of this assemblage appeared to be comparable to the deeper, siltier samples in Satellite Channel (Burd et al. 2000a), except for a much lower abundance of shallow burrowing bivalves in the Boatswain Bank area. The area was also surveyed by video to map the habitat, extent of eel-grass beds and other macro-algae (Archipelago Marine Research Ltd., 2000).

2.2.2.2 Mid-depth (30-100 m) silt/sand

Mid-depth silt/sand habitats in the SoG tend to have a broad range of organic carbon fluxes and bottom water oxygen levels. An example of the mid-depth silt/ sand habitat is found on the western side of the SoG, straddling the Fraser River discharges. Extensive biological and geochemical monitoring of these sediments has been conducted as part of the Iona outfall monitoring program for GVRD (Burd, 2000; Burd, 2003b; Bailey et al., 2003, McPherson et al., 2003, 2004b, 2005a, 2006a, 2007a), providing extensive data on both background and impacted areas (see Section 3). This area spans the Fraser River delta and hence receives the maximum influence from plume particles and bottom transported material, particularly from the south arm of the Fraser River (Hill et al., in press). Bioturbation in the area is considerable, with a surface mixed layer of up to 5-10 cm (Johannessen et al., in press). The area has a rich and diverse macrofaunal community dominated by a broad size range of bivalves, although 40- 60% of the

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total faunal abundance is contributed by one small, burrowing species, *Axinopsida serricata*. A second bivalve, *Macoma carlottensis*, comprises ~10% of the abundance. All bivalves comprise ~50% of the organismal biomass in these sediments (McPherson et al. 2006a). The remaining biomass is mostly comprised of echinoderms, primarily the brittlestar *Amphiodia urtica/periercta* complex, and a few large holothurians (*Molpadia intermedia*). Although there is a diversity of polychaete taxa present, these organisms are clearly of minor importance in the productivity of these sediments. Infaunal crustaceans are rare, comprising less than 1% of faunal abundance and far less than 1% of biomass (McPherson et al., 2007a).

The bivalve dominance evident in the 30-100m silt/sand sediments spanning the Fraser River delta, discussed above, appears to be unusual within the SoG (Burd et al., in press). Burd et al. (op. cit.) suggest that the bivalve dominance is related to the high sedimentation rates along the delta (see Johannessen et al., in press), which are less easily tolerated by infaunal polychaetes (Reid and Baumann, 1985; Burd, 2002). Brittle stars may also have an advantage in this habitat type in regard to the speed and extent of their burrowing capability. Close to the south arm discharge of the Fraser River, the sedimentation rates are too high to be measured in the standard box cores used in other locations (Johannessen et al., in press). In this location, the dominant bivalve (*Axinopsida serricata*) and the ophiuroids periodically decline, with a concurrent increase in abundance of small polychaetes typically considered to be primary colonizers (McPherson et al., 2006a). Presumably, there is therefore a limit in the ability of the infaunal bivalves and brittle stars to cope with heavy sedimentation conditions (or events).

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Although mid-depth (30-100 m) sampling stations in outer Burrard Inlet are described as having mud substrate (see earlier), several stations in this area have silt/sand substrates (i.e. stations close to the 1st Narrows bridge and near the mouth on the south side of the inlet (Fig. 1) Conversely, some areas along the bank and slope between the south arm of the Fraser River and the opening to Burrard Inlet can be classified as primarily mud. Species richness values and faunal types are similar throughout the Fraser River delta and Burrard Inlet (McPherson et al., 2006 a, b), illustrating the overlap in faunal types between mud and sandy silt habitats. However, regardless of substrate type, species abundance and biomass values have been consistently lower in outer Burrard Inlet than along the Fraser River delta (McPherson et al., 2006 a, b), and total sediment flux and organic flux are higher along the river delta than in Burrard Inlet (Burd et al., in press; Johannessen et al., in press). These patterns suggest that faunal productivity in the main basin of the SoG is more dependent on the Fraser River discharge than on substrate type or depth (Burd et al., in press).

2.2.2.3 Deep (>100 m) silt/sand

Silt/sand habitats are rare below 100 m depth in the SoG, since most of the sand (coarser, land-based material) deposits closer to shore. In most of the deeper parts of the main basin of the SoG, and at the bottom of fjords, substrates are mud (see earlier text). In the southernmost part of the main basin of the SoG, however, intense mixing throughout the water column in Haro Strait (Masson and Cummings, 2004) (see Fig. 1) may carry sandy material eroded from the southern gulf islands to the deep basin of the SoG (see also Johannessen et al., 2006), explaining why these sediments have some sand content. In addition, some of the coarse, sandy sedimenting material from the Fraser River is transported northward and downslope off the delta, ultimately

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ending up in the deep basin of the eastern margin of the southern SoG and resulting in mixed sand and silt substrates at depths greater than 100 m (McPherson et al., 2004a).

The example used to provide a description of the biota in these habitats is the area at the foot of the slope (120 m) on the south-eastern margin of the SoG, along the Fraser River discharge area. The biotic community of this area overlaps with that for the mid-depth range to some extent, but there are marked differences in faunal dominance (McPherson et al., 2004a). For example, the mid-depth bivalves, such as *Axinopsida serricata,* which are dominant from 30-100 m in the Fraser River delta and outer Burrard Inlet, decline in abundance at depths >100 m in these same areas (McPherson et al., 2004a, b, c). Brittle stars are also rare below 100 m, whereas large holothuroids such as *Molpadia* increase in abundance and the crustacean fauna changes. Number of taxa and total abundance tend to decline somewhat with increasing depth but are still relatively high at 120 m. At a location close to the south arm of the Fraser River discharge (Fig. 1) the main features of the fauna tend to be similar at depths from 60-120 m, because this entire habitat is overwhelmed by continuous high deposition of river-derived material. At 500 m north of the Iona outfall (McPherson et al., 2004b) (Fig. 1), and another location just outside the mouth of Burrard Inlet (McPherson et al., 2004a), faunal abundance and diversity decline dramatically with depth. Near the outfall, the faunal decline may be related to slumping of elevated (outfall-related) deposits along the steep slope areas. However, in both the aforementioned more northerly locations, faunal declines may be related to a combination of decreased sediment organic flux with depth and natural declines in bivalve abundance below 100 m (Burd et al., in press).

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Several stations sampled in the deep, southern basin of the SoG as part of a collaborative ambient monitoring program between the Canadian Department of Fisheries and Oceans,, Natural Resources Canada and the Greater Vancouver Regional District (Wright et al., in press) showed infaunal biomass as high, or higher, than that observed in the mid-depth zone along the Fraser River delta (see earlier text this section; Burd et al., in press). Faunal abundance and species richness were also considerably higher than those found in either of the deep, mud habitats in fjords or other deep areas of the BC coast (Burd, 1992; Burd, 2006; Burd et al., in press). At one southern SoG station, sediments had unusually high organic and inorganic flux, biomass and species richness (see Burd et al., in press) and were dominated (e.g. ~40% of total abundance) by crustaceans, particularly a cumacean (*Eudorellopsis integra*) and an ostracod (*Eudorella pacifica*); both these crustacean species were rare in the proximate mid-depth zones for this substrate type (McPherson et al., 2007a). Approximately 25% of the total faunal abundance at the same station consisted of bivalves, which is unusually high for the deep habitats, and 25% consisted of polychaetes. The remaining fauna consisted of gastropods, aplacophorans, and a few echinoderms. The second station was dominated by polychaetes with few bivalves but had a high biomass due largely to echiurans (Burd, et al., in press). A third station in the southern main basin of the Strait appeared to have a faunal composition that was intermediate between the other two stations, albeit with a lower overall biomass and abundance than the other two stations along with a lower organic flux to bottom sediments (Johannessen et al., in press). These differences illustrate the wide variety of faunal types which may occur at depth within the deep basin of the SoG, presumably related to differences in sedimentation conditions (Burd et al., in press).

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2.2.3 Sand Habitats

Unlike the previous two substrate types, sand substrates are non-cohesive and, potentially, are highly mobile. Sand habitats are abundant in areas with high energy currents and a proximate source of either land-based or glacial deposit sands. These habitats may be depositional or erosional, depending on the currents and the source and persistence of the sedimenting material. In some cases where there is on-going input of sand from erosion or freshwater runoff, the area may be net depositional with variable bottom currents. In addition, seasonal deposition of finer substrates may occur based on water column productivity, but these deposits may be resuspended and transported away during winter storms.

Sand substrates are porous and well oxygenated, often to sediment depths >10 cm; they are subject to both diffusion and lateral seepage of oxygen and dissolved organic material. Low porewater oxygen would be expected only in very unusual circumstances, such as may be found in a stagnant basin with high inorganic input. Organic flux may vary greatly but the deposition of typically fine, organic material is limited such that sediment TOC content is generally low (<1%). Sand habitats are the most extensively bioturbated of all the habitat types, as the sediments tend to be loosely packed, and, thus, are relatively easy to move through. Sand habitats may be subject to considerable transport in high energy areas, so that biotic community types and stability are directly related to the frequency and type of high energy, remobilizing events.

Biotic factors in sand substrates include a high potential for bioturbation; tube-building polychaetes and amphipods are frequently found in these substrates. Sand substrates tend to

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have a higher proportion of suspension feeders than deposit feeders, and epifaunal predators and scavengers are common. While some species that are found in the mixed silt/sand habitats may also be present in sand habitats, the strictly deposit-feeding species are typically absent or rare (Rhoads and Young, 1970).

2.2.3.1 Shallow (0-30 m) sand

In the SoG, sand substrates in depths <30 m range from being semi-protected to semi-exposed to wave and storm disrupted, and some bottom turbidity is possible. Sediment sources may be fluvial, along-shore or onshore/offshore. Predominantly sand substrates in low to moderate energy areas in the SoG typically include high numbers of deep burrowing bivalves, such as horse clams (Lauzier et al., 1998) butter clams, littleneck clams (Gillespie and Bourne, 1998). These species are common throughout BC and Alaska. Where clam populations are high, the surface sediments are commonly littered with shell debris resulting from predation. The surface of the sediments in shallow sand habitats may be dominated by sand dollars, sea pens or surface bivalves such as *Tellina* spp. (Burd, 1992). Mobile predators such as small to mid-size crabs, sea stars and drills, are common. Grazers such as small and large gastropods (such as *Gastropteron* sp.) may be present. Epibenthic amphipods can be highly concentrated, scavenging in areas of detrit. Polychaetes are common in sandy substrates, but tend to be dominated by mobile forms, which may be predators or suspension feeders. Palsson et al. (2003) note that Dungeness crab were most abundant in this depth range in the Washington State SoG (southernmost part) during the 2001 transboundary trawl survey, although they were not surveyed in this depth range in the SoG. However, there is an active crab fishery in the sandy sediments east of Vancouver Island within the southern Gulf Islands. Filamentous red and green macroalgae occur in undisturbed

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sediments and foliose red algae may be found, drifting, in the deeper areas in this habitat. In more exposed areas (or where herviborous predators such as sea urchins are abundant), encrusting coralline algae may predominate. Eelgrass beds occur in clean water, relatively low energy (i.e. sheltered) areas in these sand habitats. While the epiphytic fauna in eelgrass beds in this habitat may be similar to that found in the shallow silt/sand habitat, the infaunal communities will be composed primarily of suspension feeders rather than deposit feeders. In the deeper areas of this habitat, in specific and spatially limited patches, deep burrowing geoduck populations may be present.

An example of the shallow sandy habitat is found in Boundary Bay, which is a typical sand beach in the southern SoG (Fig. 1). Burd et al. (1987) identified 200 taxa as part of a study on the distribution and abundance of macrofauna in Boundary Bay. Most of the shallow, sand substrate stations were dominated numerically by nematodes plus several species of bivalves, amphipods and echinoderms. Polychaetes were less prominent than the aforementioned taxa. The authors note that their study illustrates the spatial heterogeneity of shallow subtidal benthic communities. Cluster analysis of the abundance data showed considerable dissimilarity between and within sand stations, particularly when compared with similar analyses for deep water benthic communities in BC (Brinkhurst, 1987). Using visual counts of specific large macrofauna along transects in Boundary Bay, Swinbanks and Murray (1981) concluded that in predominately sand substrates, tidal exposure was an important factor delineating communities. Burd et al. (1987) suggest that the spatially and seasonally patchy distribution of eelgrass in Boundary Bay (Swinbanks and Murray, 1981) is a potential factor related to the distribution patterns of species.

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Another example of a relatively unimpacted shallow sandy habitat was studied on the western margin of the Strait, just north of Saanich Inlet (Boatswain Bank). This location was discussed earlier (under shallow silt/sand habitats; section 2.2.2.1), and included both habitat types along an on-shore/offshore gradient, with sandy substrates in the shallower subtidal region.. Epifaunal biota and macroalgae (Seacology et al., 2001) and infauna (Burd and Glaholt, 2000) were surveyed along several transects perpendicular to shore at the proposed SoG crossing pipeline landfall site. Eelgrass beds and other macroalgae were mapped more extensively in the area by video survey (Archipelago Marine Research Ltd., 2000). The sandy stations were all found at less than 10 m depth, below a typical cobble intertidal beach, and were dominated by infaunal bivalves and crustaceans, along with polychaetes and a few echinoderms within patchy eelgrass beds. The authors noted that juvenile fauna were numerous, which would be consistent with the concept that eel-grass beds are important nursery grounds for many types of fauna (Archipelago Marine Research Ltd., 2000).

2.2.3.1 Mid-depth (30-100 m) sand

Mid-depth sand habitats in the SoG are subject to a variety of wave exposures, are often affected by currents or swells and may be influenced by large storm events. Bottom turbidity is usually low in these sand substrates, however, because these sediments are heavy and settle quickly. The biota found include burrowing bivalves that may be smaller, on average, than those found in the shallower sand habitats. Burrowing polychaetes and mat-forming tubicolous polychaetes occur in mid-depth sand habitats, as do ophiuroids, although these are found in lower abundance than in finer grained habitats (Burd et al., 2000a; McPherson et al., 2007a). Crustacean fauna are an important component in these habitats and depths, including Dungeness crabs (Palsson et al.,

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2003). Sea pens and sea whips are found in higher current areas (Burd, unpublished data) and some attached forms of invertebrates (e.g. hydroids) occur on larger fauna and debris (V. Macdonald, pers. comm. Biologica Environmental Services Ltd, Victoria, BC).

The mid-depth sandy habitat type example from the SoG is the Ecological Reserve 67, located in Satellite Channel. Although an Ecological Reserve, this area was neither regulated nor subject to enforcement until several years ago. However, the only major impact on the area has been bottom trawling and, despite the known biotic changes that can occur in areas of concentrated bottom trawling (Engel and Kvitek, 1998; and see Conservation Biology issue 12: Vol. 6, 1998), a reconnaissance survey in 2000 for the proposed GSX pipeline suggested that the benthic biota are typically diverse and abundant compared with other areas of the SoG (Burd et al., 2000a; Burd et al., in press). Fauna in the reserve are dominated by bivalves and a mixture of mobile and non-mobile polychaetes (epibenthic and burrowing, free-living and tube-dwelling); the latter group may have comparable or lower abundances than the bivalves. The fauna also includes abundant crustaceans but relatively few gastropods. Echinoderms are rare which may be because large, mobile organisms with patchy distribution are not readily sampled using the methodology (grabs) of the studies cited here or, alternatively, the low abundance may reflect the adverse effects of bottom trawling. Older studies of the same area suggest that echinoderms were more common in the late 1960s (Ellis, 1970; 1971), before bottom trawling was frequent in this area. Ophiuroids also are relatively rare, which may be related either to the non-selective deposit-feeding habits of these animals and the lower organic content of sediments or, again, to the damage caused to these near-surface fauna by bottom trawling. Mats of tube-dwelling polychaetes *Galathowenia oculata* and *Owenia fusiformis* were abundant in the Satellite Channel

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area in the late 1960s (Ellis, 1970, 1971), but were not abundant in 2000 (Burd et al., 2000a). Bottom trawling is likely to cause disruption of tube mat structures on the sediment surface. Largely because mid-depth sand habitats typically have moderate sediment oxygen levels and low turbidity, hydroids are found attached to shelled organisms on or just below the surface (Burd et al. 2000a), and may be an important component of the filter feeding biota of these habitats.

During the 2001 PICES Burrard Inlet workshop, fauna were sampled from a mid-depth sand habitat reference station outside the sill of Howe Sound (PICES, 2001; Je et al., 2003). Results using similar sampling methods showed species richness at this station was similar to that of samples from the ER67 Satellite Channel stations (Burd et al., 2000a; Je et al., 2003). Faunal abundance, however, was much higher in the Satellite Channel samples, as there were fewer bivalves present in the Howe Sound location. Polychaetes, rather than bivalves, were dominant at the Howe Sound location. A range of epifaunal types (8 taxa) are listed in Bernard (1978) to occur at depths of 20-100 m in sandy areas sampled in the SoG.

2.2.3.1 Deep (>100 m) sand

Deep sand habitats only occur, typically, in moderate to high current (erosional) areas. In low current areas, the deposition of fine marine detritus would cover the sands eventually. The epi-benthic list of Bernard (1978) includes 4 taxa for the 100-200 m depth range but only one polychaete (*Pectinaria californiensis*) is listed for the 200-300 m depth range and one scaphopod (*Dentalium rectius*) for the 300-400 m depth range Although no other data or studies are available from such habitat types in the SoG, these sand habitats may occur in deep water in

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isolated areas near the southern Gulf Islands or in the northern half of the SoG (Fig. 3). Information on the biotic communities in these habitats outside the SoG, specifically in Hecate Strait and la Perouse Bank, is available in Burd and Brinkhurst (1987) and Brinkhurst (1987), respectively.

2.2.4 Cobble, Gravel and Coarse Sand Habitats

Cobble, gravel and coarse sand habitats are usually found in moderate to high energy locations. This substrate can also occur, however, where there are coarse glacial deposits in lower energy locations with no source of finer glacial or freshwater-derived inorganic particulates (finer sands). These substrates can be both mobile and immobile. For example, constant deposition of substrate material from a major land-based source would probably lead to unstable deposits subtidally, particularly on slopes. In stable habitats, however, these substrate materials tend to be heavy and can only be moved by high energy waves or storm events, particularly in shallow subtidal areas. Similarly, the coarse materials are a difficult substrate for the burrowing activities of bivalves and other fauna and, as a result, bioturbation may be limited. Because the substrate materials in these habitats are so coarse, sediments tend to be well-flushed and oxygenated. The benthic fauna are dominated by suspension feeders and mobile predators, particularly in high current areas. Cobble substrates in particular are likely to have fauna similar to rocky substrates (Section 2.2.5).

Bernard (1978) includes a few dominant epifauna from these habitats at various depths, but the epifauna list is short relative to that for soft substrates due perhaps to the difficulties in sampling

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this habitat type. These habitats can be viewed as "intermediate", as they are neither soft enough for effective grab samples to be taken nor flat and smooth enough for visual transect surveys. Much of the fauna is interstitial (ie. living between sediment particles) and there is no efficient way to sample them. Similarly, while trawls may collect some epibenthic forms, both the nets and the captured biota are prone to damage by cobble and gravel substrates. Bottom sampling is further hampered by the fact that these habitats are usually very high current areas. Hence, there is very little information about these habitats in the SoG, and none of the information available is quantitative.

2.2.4.1 Shallow (0-30 m) cobble, gravel and coarse sand

In shallow depths in the SoG, these coarse substrates are found most often on high energy or exposed to semi-protected areas, extending from the intertidal to the shallow subtidal. An example of such a habitat is given in Seacology et al. (2001) and Burd and Glaholt (2000), but it is noted in both studies that the cobble or gravel does not extend very far below the intertidal, and tends to occur in patches along with coarse sand. These habitats are usually non-depositional but may be influenced by seasonal onshore/offshore movement of material due to storm events and strong currents. In addition, periodic storms may lead to patches of storm or tidal debris (organic and inorganic) which are usually transitory. If these shallow habitats are not too high energy, seasonal macroalgae such as the brown algae *Laminaria, Costaria* and *Desmarestia* may be dense along with patches of bull kelp (Seacology et al., 2001) along with epifaunal grazers. A variety of mobile epifauna are found in these habitats, including amphipods, sea stars, nudibranchs, gastropods, echinoids and large mobile polychaetes, shrimp and crabs, and is also noted to be a nursery habitat for juvenile Pacific cod. Sessile invertebrates attached to the larger

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substrate particles include bryozoans, hydrozoans, small sponges and anemones. If the sand content is high, deep burrowing bivalves may occur. However, in larger particle mixes (gravel, small cobble), near-surface bivalves may be common, and shell debris extensive. Coarse, unconsolidated habitats, if stable, can have extensive macroalgal growth seasonally, with all the associated grazing, epiphytic and epifaunal biota associated with it. Typically, this may include extensive bryozoan (in shallow, near-subtidal) and hydrozoan growth, shrimp, crabs, amphipods and other crustaceans, nudibranchs, gastropods, sea-stars and sea-urchins, with anemones, small sponges and tunicates attached to larger, stable debris. One common bivalve which can be seen "walking" through coarse sands is *Tellina* sp., which can be found intertidally to subtidally in Hecate Strait and throughout southern Alaska, BC and Washington State. Other, larger echinoderms may be present in coarser debris, such as the sea-cucumber *Parastichopus* sp.

2.2.4.2 Mid-depth (30-100 m) cobble, gravel and coarse sand

Cobble, gravel, and coarse sand habitats below 30 m water depth are rare in the SoG, with the exception of very high energy environments such as tidal channels, on fjord sills, and high current areas. Because of the size of the substrate particles, these habitats are relatively physically stable, although they may be mobile in rare, large storm events. Suspended particles may be extensive, given the high energy nature of these habitats. Generally, the faunal community in these habitats includes mobile epifauna (e.g. sea stars, nudibranchs, gastropods, amphipods), as well as 'surface film" grazers and attached forms (e.g. hydroids, small sponges, anemones) on the larger sediment particles (see Farrow et al., 1983).

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An example of mid-depth coarse habitats is the sill of Knight Inlet, which is located immediately north of the SoG. The Knight Inlet sill is also a tidal channel, with coarse sand, gravel and large boulders which can be moved by the strong tidal currents (see Farrow et al., 1983). Tunnicliffe and Syvitski (1983) describe how large gorgonian corals attached to boulders provide "windage" which contributes to the transport of boulders in this area. The authors found that these rare habitats may contain typical rock cliff epifauna occurring in patches but, unlike cliff fauna, the forms are usually encrusting which may be related to the potential physical damage caused by the moving boulders and high currents. The distribution of the large planktivorous corals was patchy but the organisms were most concentrated on the sill crest, where the zooplankton were visually dense (Tunnicliffe and Syvitski, 1983). The level of heterogeneity within this type of habitat will determine the abundance of small mobile fauna that like to hide, such as shrimp and small crabs.

Although the extensive outfall monitoring program in outer Burrard Inlet focused on soft substrate, video assessment of the nearfield substrate revealed the presence of cobble, gravel and coarse sand substrate (CORI, 2002). Flocculant levels were high in the water column, reducing visibility. However, large concentrations of the anemone *Metridium senile* suggested opportunistic utilization of the suspended organic material (CORI, 2002). Visual surveys by the Victoria Capital Regional District describe the 40-60 m depth range off southern Victoria near Clover Point (just outside the SoG, in Juan de Fuca Strait) as cobble-gravel, with extensive horse mussel and scallop growth (Capital Regional District, 2000). Bernard (1978) listed 2 bivalve species, (*Glycymeris subobsoleta* and *Mysella tumida)* sampled by trawl from gravel substrates and 6 different species found in rock/cobble substrates.

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2.2.4.3 Deep (>100 m) cobble, gravel and coarse sand

These coarse grained habitats seem to be rare in the deeper parts of the SoG (Fig. 3). It is likely that these habitats are limited to the few deep, strong tidal channels in the SoG at the north and south end (Section 1.2) and to areas where debris resulting from cliff erosion has settled at the foot of steep slopes. These areas have been observed, occasionally, using a submersible (Burd, unpublished data) and, although most fish farms in BC are located outside the SoG, information on these habitats under fish farms in the fjords of the SoG may also be archived in ROV video footage maintained by the provincial Ministry of Environment.

There is very limited information about these coarse habitats and associated biota in depths >100 m within the SoG. However, it is expected that the faunal communities would be of similar composition to those described earlier for the mid-depth coarse habitat. The only caveat is that at these depths, it is likely that organic flux to the bottom is reduced, so that there may not be as much labile organic suspended material available for bottom organisms. Bernard (1978) describes invertebrate epifauna from trawls conducted at 100-200 m depths in gravel habitat type and lists the same two species found in the 20-100 gravel substrates, the bivalve *Glycymeris subosoleta* and the crustacean *Munida quadrispina*. The author lists no species for sampling conducted in gravel substrates >200 m. Invertebrate species were more abundant in the rock/cobbles substrate than in the gravel substrate, but only the cloud sponge *Aphrocallistes vastus*, was reported from the rock/cobbles substrate type at >200 m depths. As noted earlier,

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archived information on videos from deep ROV work related to fish farms may be one of the best sources of epifaunal data available.

2.2.5 Rock (consolidated) Habitat

In exposed coastal areas, these substrates are subject to very high wind and wave exposure and/or tidal currents, preventing any deposition. However, in isolated basins such as fjords, the steep sides prevent accumulation from sedimentation regardless of current conditions. Some island archipelagos, with no freshwater or nearby glacial deposits, can retain rocky substrates in lower energy habitats. Although high levels of suspended organic particles occur, depending of the current regime and organic input, organic flux to the sediments if virtually nil.

Rocky habitats are abundant in the SoG and Levings et al. (1983) note that rocky and sandy shores combined make up 88% of the total length of the shoreline (shoreline consists of the intertidal and subtidal habitats $\leq$20 m), while the area of rocky substrate accounts for ~25% of the total area (see Section 1.3.1). Many of the SoG's mainland fjords have extensive, near-vertical rocky cliffs, limiting the fauna to those that can attach to vertical rock and that can tolerate sediment deposition. These rock wall communities are dominated by sessile filter feeding invertebrates or mobile scavengers and predators. Tidal currents in these habitats are usually low due to the near-vertical walls which don't "channel" or intensify tidal surges.

2.2.5.1 Shallow (0-30 m) rock (consolidated)

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The diversity and coverage of rocky shoreline communities is dependant on exposure to waves, freshwater, salinity, light and currents and is, therefore, seasonally variable. The presence of crevices or heterogeneous structure for hiding and attachment also affects both the plants and invertebrates found in these shallow rock habitats. The bottom water in these habitats is usually highly oxygenated. If there is a rich supply of suspended particulate material, these areas can be ~100% covered by sessile invertebrates and plant growth. Seasonal macroalgal cover of filamentous and bladed red, green and brown algae is extensive in the upper photic zone, with foliose reds commoner in slightly deeper areas (i.e. >10 m).

The fauna found in these habitats, both sessile and mobile forms, tends to be relatively consistent throughout the BC coast. The diverse fauna in these habitats includes bivalves, calcareous tube worms, ascidians, bryozoans, hydrozoans, small sponges, as well as echinoderms and crustaceans. Because these rocky habitats have been so well described by scuba surveys at these shallow depths, the flora and fauna are not described in detail herein (e.g. http://ilmbwww.gov.bc.ca/lup/coastal/north_island/cortes/docs/2-description.pdf; Levings et al., 1983 and references therein). An example of a shallow rock habitat just outside the SoG is Race Rocks, near Sooke, BC. Race Rocks, a tidally-exposed rocky outcrop in a “clean” environment which has been well studied using SCUBA. The area has a remarkably rich and diverse flora and fauna (see Wright and Pringle, 2001 for references) and is a federal marine protected area. The invertebrate fauna tolerates strong currents and high wave exposure and includes abundant barnacles, goose-neck barnacles, and mussels, as well as a variety of anemone species, surface-grazing gastropods, mobile predators such as sea-stars, nudibranchs, crabs and gastropods.

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Shallow rock habitats may be structurally heterogeneous as a result of algal growth and also from faunal communities such as mussel beds. Up to 300 species have been identified inhabiting the interstices of established mussel beds (Seed and Suchanek, 1972; Suchanek, 1979) and species richness has been shown to increase with increasing age and thickness of the mussel bed (Asmus, 1987; Jamieson et al., 1999; Ragnarsson and Raffaelli, 1999; Smith et al., 2006).

In the deeper, high current areas of shallow rock habitats, bull kelp can form dense forests which modify currents and light penetration and provide important refugia for fish, as well as food for sea urchins and other grazers. Sea urchins are known to be a key species which controls and modifies algal community associations in near-shore rocky habitats on the west coast of North America (Paine and Vadas, 1969; Duggins, 1981). Abalone may play a similar role but tend to be less widely distributed in BC coastal waters than are sea urchins due to excessive fishing pressure over the years (http://www.dfo-mpo.gc.ca/species-especes/species/species northernAbalone_e.asp).

2.2.5.2 Mid-depth (30-100 m) rock (consolidated)

Mid-depth rock habitats in the SoG typically have moderate to steep slopes; accumulation of deposited material is unlikely to occur on steep slopes but pockets of deposition may occur on lesser slopes. These habitats are exposed to limited, or no, wave exposure, while levels of tidal currents vary. Bottom water renewal, and therefore bottom water oxygenation, in these habitats

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in the SoG is variable and depends on the physical topography and, in fjords, also depends on the depth of the sill.

Because these habitats can only be studied using ROVs or submersibles, they are, therefore, less well studied than soft substrate habitats at comparable depths. The majority of this research in the SoG was conducted in the early 1980s, when the research submersible PICES IV was available through the Canadian Department of Fisheries and Oceans. Much of this research is published (e.g. Tunnicliffe, 1981; Levings et al., 1983; Tunnicliffe and Wilson, 1988) and additional, unpublished information is archived in video or still photographic form (Tunnicliffe, unpublished; Burd, unpublished). The following general descriptions of the faunal communities in the mid-depth rock habitats of the SoG are based on both sources of data.

The spatial cover by invertebrates in the mid-depth rock habitats does not vary as much seasonally as it does in shallow subtidal areas. However, there may still be some encrusting coralline algae present at the shallow end of this depth range, depending on light penetration (e.g. Farrow et al., 1983; Spalding et al., 2003). Rather, the spatial cover by invertebrates declines with increasing depth and decreasing oxygen levels in the water. Examples of the mid-depth rock habitat are the rock cliff walls of fjords in the SoG. These mid-depth habitats contain a number of species, such as eel-pouts, that are more common in the deep sea. Similarly, sea fans (gorgonians, soft corals) are common on the walls of some of the SoG inlets (Tunnicliffe, 1981; Tunnicliffe and Wilson, 1988) but are also found when sampling in the deep water off the continental shelf. Huge glass sponges, normally associated with polar or deep seas, are also common in mid-depth rock habitat in the SoG fjords (Tunnicliffe, 1981; Burd, PICES IV–

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unpublished data). Tunnicliffe (1981) describes tube worms, sponges, brachiopods, cup corals, extensive gorgonian sea fans, anemones and colonial tunicates as some of the dominant sessile organisms on the vertical rock walls. Some of the larger sponge and erect coral growths are expected to be very old, as these habitats are typically less susceptible to physical damage than are level bottom habitats.

Tunnicliffe and Wilson (1988) describe the distributions of 3 species of brachiopods from Knight, Jervis and Saanich inlets; brachiopods are a ubiquitous group reaching extremely high densities (average density of 190/m^2, maximum density of 945/m^2) at depths >30 m on the cliff walls of the fjords. Depth ranges were noted for each species of brachiopod. All brachiopod species seem to be relatively tolerant of low oxygen and a species in Saanich Inlet was found to be highly tolerant of periodic low oxygen levels down to 0.1 ml/L. Another brachiopod species from Saanich Inlet was found in abundance in high energy and/or high suspended sediment conditions. Thus, brachiopods are an important structural component of mid-depth cliff faunas and may be good indicators of sedimentary conditions. In contrast to brachiopods, bivalves are almost absent on the vertical cliff walls, suggesting that they do not settle on vertical surfaces. In addition, as a group they do not seem to be particularly tolerant of low oxygen (see also Burd, 2006).

Several mobile crustaceans are common on, or near, the rocky cliff walls of the fjords at mid-depth. These areas encompass the prevailing prawn fishery habitats, as the larger pandalid species tend to be abundant in the rocky crevices and on larger, upright epibenthos. Predatory crabs are less common in this depth range than in the shallow rocky cliff areas, (Burd, unpublished), however, a small anomuran crab (*Munida quadrispina*), with feeding and habitat

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requirements similar to prawns co-exists with the prawns on the cliffs (Burd and Brinkhurst 1984). Examination of prawn catches and habits of prawn fishermen in a series of coastal fjords in the SoG in 1983/84 (Burd, unpublished) made it clear that when *M. quadrispina* were dominant, this necessitated a change in the location for setting traps.

Saanich Inlet and Howe Sound, as noted earlier, can experience severe annual stagnation and this can lead to mass mortalities of sedentary cliff fauna (Tunnicliffe, 1981) as well as mobile forms such as prawns and *Munida quadrispina* (Burd and Brinkhurst, 1984; Jamieson, 1988). Tunnicliffe (1981) described a high biodiversity in the mid-water cliff assemblage of Saanich Inlet, however, despite annual low oxygen, *M. quadrispina* is usually far more abundant in extreme habitats, such as the very low oxygen areas (~0.1ml/L) in Saanich Inlet (Burd and Brinkhurst, 1984) than in areas with higher oxygen levels. The higher abundance (and lack of normal territorial and hiding behaviour) of the crabs has been speculated to be related to a lack of predators in these extreme habitats (Burd and Brinkhurst 1984), whereas the tolerance of very low oxygen areas is due to unusual respiratory and gill adaptations (Burd, 1985, 1988). In addition, the pelagic amphipod *Orchomene obtusens* is found in extremely high numbers on, or near, the rocky cliffs in hypoxic to anoxic conditions in Saanich Inlet (De Robertis et al., 2001), where it is extremely efficient at consuming any detrital animal tissue used as bait in traps (Burd, unpublished data).

Farrow et al. (1983) describe the fauna of the cliff walls in Knight Inlet along vertical cliff transects which include the mid-depth zone. The along-inlet differences in faunal structure were compared with a suspended particulate gradient which typifies the faunal changes that are likely

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to occur in areas of high, moderate, and low bottom turbidity from glacial runoff. In the high turbidity areas, the authors describe the dominant suspension feeders as sabellid worms and brachiopods (see also Tunnicliffe and Wilson, 1988) which take small particles (<8 µm). Crinoids and gorgonian corals are more prevalent in the moderate tubidity areas and take larger particles, while barnacles and glass sponges predominant where turbidity is low. In general, the turbidity, oxygen and organic carbon content of suspended particulates within these habitats play a significant role in determining which species will dominate. For example, brachiopods are tolerant of relatively low oxygen conditions and can also tolerate relatively high turbidity. Passive feeders, such as sponges, require some current movement for adequate feeding, but may be tolerant of low oxygen (e.g. Tunnicliffe, 1981), and are usually found in deeper regions in more quiescent waters (Tunnicliffe, 1981; Farrow et al., 1983) with limited sediment deposition (Farrow et al., 1983 and see below).

A bottom hexactinellid sponge reef has been recently discovered at an unprecedented shallow depth of about 60 m near the sill of Howe Sound (see Cook et al., in press). Most of these reefs in the Strait are deeper than 120 m, making this location unusual. This reef has not been visually surveyed yet. A description of other, deeper reefs in the Strait is given in the next section.

2.2.5.3 Deep (>100 m) rock (consolidated)

While deep subtidal rock habitats in the main basin of the Strait of the Georgia are mostly confined to elevated rocky outcrops on the bottom of the basin (evident in detailed multibeam and side-scan sonar transects e.g. Conway et al., 2007), these habitats are often dominant in

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many of the steep-sided fjords. Many of the SoG fjords are much deeper (up to 800 m) than the adjoining continental shelf (<400 m deep), with extensive rock cliffs. The same limitations for studying the mid-depth rock habitats, discussed earlier, apply to these much deeper habitats.

In deep rock habitats that are "flushed", bottom currents are generally low to moderate. Bottom water oxygen is likely to be moderate. Spatial cover of sessile invertebrates on these "flushed" rock substrates is moderate to low, declining with increasing depth and decreasing oxygen levels and is also related to current levels. The faunal composition does not necessarily change significantly from that described for mid-depth rock habitats except that, as suspended organic material and oxygen levels decline with increasing depth, spatial coverage may decrease and some organisms or trophic forms may decline while other, more tolerant forms increase. For example, as noted earlier, prawns decline with increasing depth and anemones such as *Metridium senile* are not found below 80-100 m (Tunnicliffe, 1981; Burd, unpublished data). The faunal community may include calcareous tube worms, brachiopods, ascideans, hydrozoans, small sponges, boot and cloud sponges, gorgonian and small corals, large plumose anemones and tunicates.

It should be noted that deep rock habitats in the SoG are also found on the walls of isolated fjords in stagnant basins. The water column in the deep rock habitats in the fjords may flush seasonally or only occasionally. Generally, the rock may be too steep for sediment accumulation but small pockets of organic material may accumulate in crevices and became suboxic or anoxic with filamentous bacterial mats. In these low current areas, the rock is usually minimally colonized with numerous areas of bare rock. As mentioned for mid-depth rocky areas, the fauna

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in these deep stagnant areas may include small anemones, encrusting sponges and brachiopods, as well as specialized mobile predators (e.g. amphipods, *M. quadrispina*) (Burd and Brinkhurst, 1984).

An interesting example of the deep, rocky habitat is the relatively recently discovered deep rocky outcrops or reefs in the SoG that are covered in hexactinellid sponges (predominantly *Heterochone calyx* and *Aphrocallistes vastus*) or in a few cases, scleractinian coral reefs (*Lophelia pertusa*) (Conway et al., 2007). There are nine confirmed glass sponge reef complexes in what Thomson (1998) describes as the central Georgia Basin (Fig. 1). Each of these sites has been surveyed using multibeam acoustics and ground truthed using remote video techniques by the Geological Survey of Canada. There are a further 3 sponge reefs which have been located by multibeam and seismic surveys but which have not yet been visually examined using video (Conway et al., 2007). Of the nine reefs which have been visually surveyed, only three are in good health, with consistent areas of live reef-building sponges (Cook et al., in press). The three healthy reefs are located on rock pinnacles well above the surrounding seafloor, where bottom trawling is not feasible. The other six appear to have suffered extensive mechanical damage resulting in large areas of fragmented sponge skeleton, with 3 reefs showing some evidence of re-growth. (Cook et al., in press).). Conway et al. (2007) concluded that there has been considerable damage to the reefs in the SoG from trawling and possibly from ocean dumping and increased siltation in the southern areas. There is a marked difference in terms of abundance and diversity of rockfish on the healthy and damaged reefs, illustrating that these are likely important refugia for deep reef fish. An ecological description of these reefs is in Cook et al. (in press), including the current state of their health and faunal associations.

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It is well documented that hexactinellid sponge communities, such as those found in deep rock habitats in the SoG, modify the environment around them. Bathyal environments in particular are enriched by enhanced supplies of organic matter associated with sponges and their spicule mats (Bett and Rice, 1992). In the Antarctic, Barthel, (1992) documented species-rich associations of sponges in areas of sponge spicule mats. These reefs trap fine sediments and provide habitat for annelid worms, bryozoans, bivalves, gastropods, rockfish, crabs, shrimp, prawns, sea stars, sea urchins and ophiuroids. In other areas of the world, hexactinellid sponges provide habitats for new and rare species, including numerous species of shrimps in the Bahamas (Berggren, 1993), Hawaii (Baba, 1983), New Zealand and South Africa (Bruce and Baba, 1973), and in the East China Sea (Hayashi and Ogawa, 1987). Their locally limited distribution and potential biological importance as refugia in the SoG warrant protection (Conway, 1999; Conway et al., 2001; Krautter et al., 2001).

Underwater cables provide hard substrate in deep water, albeit of anthropogenic origin. Levings and McDaniel (1974) describe encrusting macro-invertebrates collected off a deep-water telephone cable across the main basin of the SoG. This habitat appears to be a “refugia” containing fauna that are found on the steep rocky cliffs of the surrounding basin shoreline. The authors note that most of the deeper, hard-substrate species such as sponges, brachiopods and gorgonian corals were not present on the cables on the eastern side of the SoG (Point Grey), probably due to heavy sedimentation from the Fraser River. Even in these high sedimentation areas, however, several anemones, such as the ubiquitous and relatively tolerant *Metridium senile*, were found on the cables.

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3. Anthropogenic Influences

Section 2 reviewed invertebrate communities likely to occur in a variety of undisturbed habitats (different depths and substrates) within the SoG. In this section, changes to habitats and invertebrate fauna found in areas of anthropogenic influence are examined and placed within the context of background biotic conditions in the SoG. Following a brief summary of anthropogenic sources and recognized influences of the type of major sources in the SoG, additional detail is provided on each source including case studies where appropriate. It should be noted that while input from some anthropogenic sources may affect intertidal or shallow subtidal areas, most of the major discharges into the SoG are deeper than the shallow subtidal (i.e. >30 m) and, consequently, habitats monitored for anthropogenic change also tend to be >30 m depth (mid- to deep subtidal).

The primary sources of anthropogenic influence in the SoG are municipal waste water outfalls (marine and along the Fraser River), ocean dumping sites (dredged material primarily from Burrard Inlet and terminal areas along the eastern margin of the southern Strait), pulp and paper mills, as well as runoff and discharges from agriculture and other industries along the Fraser River and Burrard Inlet. Localized sources of anthropogenic influence to marine habitats within the SoG include a small number of fish farms in several mainland fjords, log-booms, marinas, loading docks for industry, and stream runoff. While a large number of beach and near-shore shellfish aquaculture sites are located in the SoG, research into the potential impacts of these farms on benthic habitats and invertebrate community structure started only recently (e.g. Carswell et al., 2006) and, hence, the potential impact of these farms is largely unknown.

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Although the biotic effects of these localized small inputs can be varied and difficult to encapsulate, available studies on these inputs are summarized briefly in this review (and see Levings et al., 1983).

Although the majority of the anthropogenic influences in the SoG include an organic enrichment component, virtually all of these influences also include some level of sediment contaminants which can make it difficult to determine causality. A huge literature on sediment and pore-water toxicity, much of it laboratory-based, illustrates the on-going struggle with these issues in the scientific community (Wang and Chapman, 1999; Burgess, 2000; Long et al., 2001). Burrard Inlet, the major harbour for Vancouver, provides an example of a body of water in the SoG that is subject to numerous sources of anthropogenic input. The proceedings of an international, cooperative research workshop in Burrard Inlet (Stehr and Horiguchi, 2001) include a summary of the discharges and contaminant sources in the inlet (Levings and Samis, 2001). This inlet receives the discharge from a major primary-treatment municipal wastewater outfall, about 32 combined sewer overflows (CSOs) (GVRD, 2004), and 36 permitted industrial or municipal discharges (Levings et al., 2004). Several of the more isolated sections (or arms) of Burrard Inlet are considered to be severely chemically polluted by hydrocarbons (Yunker et al., 1999) and organically enriched (Burd and Brinkhurst, 1990). The multitude of discharges, along with complex hydrographic conditions, has made the design of monitoring programs for specific discharges in the Inlet challenging (c.f. McPherson et al., 2007b). Similarly, Howe Sound has been subject, historically, to notable industrial inputs including a chlor-alkali plant (mercury discharge) and a copper mine with contaminated tailings and acid drainage issues which are still evident many years after cessation of operations (Hagan et al., 2004). Contaminant inputs and

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transport from these sources were reviewed by Macdonald and Crecelius (1994), West et al. (1994) and see Johannessen et al. (in press).

Despite the confounding influences described above, however, certain patterns of benthic faunal response seem to be common to all organic enrichment inputs in British Columbia regardless of contaminant input (Cross, 1990; Burd, 1997; Brooks, 2001; Burd 2003a,b,c; Cross et al. 2005; Golder Associates Ltd., 2005; Burd, 2006; McPherson et al., 2007a, b; EEM monitoring data www.ec.gc.ca/eem/english/PulpPaper/default.cfm;).

Biotic responses in marine sediments to conditions resulting from extreme organic loading have been described by Pearson and Rosenberg (1978). Based on this model, when sulphides are high and/or sediments are anoxic to depth, most fauna disappear. When these sediment conditions occur, white fibrous mats of sulphur-fixing bacteria (e.g. *Beggiatoa* spp.) may become extensive on the seafloor. In addition to high sulphides, however, the bacteria need oxygen from the overlying water for metabolism and, therefore, these mats occur only at the oxidation-reduction (redox) boundary (Møller et al., 1985), making them a good indicator of underlying anoxic sediments or, in rocky areas, of an anoxic near-bottom boundary layer. In fact, the presence and extent of *Beggiatoa* mats is used as a monitoring indicator of benthic condition for fish farms in BC (MWLAP, 2002). The few organisms that can survive, or sometimes even thrive, in these conditions include certain mobile epibenthic forms such as demersal amphipods and squat lobsters (Burd and Brinkhurst, 1984), as well as burrowing organisms that can maintain access to the oxygenated overlying water, some of which may have a high tolerance to sulphide (Brooks, 2001). Despite these organisms, however, infaunal production is typically low in extreme environments due to loss of most of the macrofauna and energetic constraints on microfauna

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utilizing energy resources without available oxygen (Emerson and Hedges, 2003). In rocky habitats, most fauna will disappear, with the possible exception of some tolerant cup corals (Tunnicliffe, 1981). Examples of benthic environments in the SoG where anthropogenic inputs causing these conditions may arise or have been recorded include municipal wastewater outfall receiving environments (Capital Regional District 2003; 2004; 2005 and www.crd.bc.ca/wastewater/marine/reports.htm; McPherson et al., 2007a, b); log boom areas (Conlan and Ellis, 1979; Sibert et al., 1979; Sibert and Harpham, 1979; McGreer et al., 1984), the close vicinity of some fish farms (Brooks, 2001; Burd, 2006; Wright et al., 2007a-e), and areas subject to pulp and paper mill effluent (www.ec.gc.ca/eem/english/PulpPaper/default.cfm). These extreme conditions can also occur naturally in stagnant fjord basins (e.g. Saanich Inlet, Section 1.2).

3.1 Marine Outfalls

Benthic sediment and biological monitoring for the marine receiving environments of the Metro Vancouver (formerly the Greater Vancouver Regional District GVRD) outfalls that discharge into the SoG (Iona and Lions Gate) also encompasses the marine discharge zones of the other three outfalls along the Fraser River (Annacis, Lulu Island and Langley - GVRD 2004). These monitoring programs have essentially provided the bulk of present-day information about benthic infauna and habitats along the southeastern margin of the SoG (see McPherson et al. 2007a, b). The Iona outfall monitoring grid is along the 80 m depth contour (Figure 1) straddling the mouths of the Fraser River. The Lion's Gate monitoring grid encompasses all of the outer Burrard Inlet to 1st Narrows (Figure 1).

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Harrison et al. (1999), reviewing the heavy metal and organic contamination along the foreshore of the Fraser River, found that most of the contamination in this area came from heavy deposition of Fraser River sediments which had run the gauntlet of contamination sources. However, at the north end of the delta, there was a fairly large historical (1962-1988) wastewater discharge in the near shore. Harrison et al. (1999) showed that in the area of historical wasterwater discharge (which also receives about 15% of the industrial and municipal wastes from the Fraser River), there is evidence of long term recovery in terms of organic loading, as well as primary and secondary production of the benthos. Two moderately abundant invertebrate indicators, the amphipod *Corophium salmonis* and the bivalve *Macoma balthica*, were selected for measurements of biomass/production and growth, and were used to demonstrate the recovery from basically azoic conditions (i.e. no life) to background conditions typical for the area. The historical wastewater discharge noted above was replaced in 1988 with the Iona deep-sea outfall, with diffusers which discharge along the slope fronting the Fraser River discharges.

The deposition model of Hodgins and Hodgins (2000) for the Iona outfall effluent solids suggests that maximum deposition of outfall particulates occurs between 60-90 m depth along a primarily north and secondarily south gradient away from the outfall. This model provided the basis for a revised monitoring program for the outfall from 2000 onward (2WE Consulting, 1999). The maximum deposition zone corresponds to clear patterns in sediment chemistry and geochemistry, including moderate organic enrichment (Burd, 2003b). The long-term monitoring data for Iona (see McPherson et al., 2007a) clearly show subtle changes in biotic conditions within a 3 km zone north of the outfall, which corresponds to the maximum deposition zone for outfall particulates (Hodgins and Hodgins, 2000). Within this same area, clearly related to the

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outfall, there is low to moderate biotic impoverishment (GVRD, 2004) and a modest enhancement of polychaete species know to be opportunistic in areas of organic enrichment. These changes can be explained by increased organic loading alone, with no evidence of biotic effects related to contaminants (Burd, 2003b). Certain contaminant inputs from the outfall are discussed in more detail in Johannessen et al. (in press) and Macdonald et al. (in press). Surrounding the impoverished zone is a region with less deposition of particulates that has no notable biotic impoverishment and shows enrichment of some taxa. Echinoderms and crustaceans, the taxa which are most impoverished in the maximum deposition zone, tend to have enhanced abundance in this enrichment zone (Burd, 2003b; McPherson et al., 2007a).

To the south of the outfall, where no outfall particulates deposition can be detected, a range of background biotic conditions provides context for the changes found within the two "effect" zones. Interestingly, however, biotic impoverishment within this background area can be similar to, or greater than, that found in the maximum deposition zone. This impoverishment does not co-occur with organic enrichment, or any contaminant loading, but seems, rather, to be characteristic of on-going and patchy physical disturbance of the sediment surface (Burd, 2003b, McPherson et al., 2004b).

McPherson et al. (2007a) includes a time-scale comparison of biotic and geochemical conditions which clearly show that both have remained relatively stable throughout the Iona outfall monitoring region since 2000, including consistently low total organic carbon levels in sediments throughout the monitoring grid, along with modest geochemical buildup of sulphides in the maximum deposition zone The reason for the uniformly low organic carbon levels is mostly the

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high loading of inorganic material from the south arm of the Fraser River, which tends to continually bury the organic input, keeping the entire system in a relatively steady state. However, rapid oxidation of carbon at this location (Wright et al., in press) from benthic organisms may also contribute to the stable sediment conditions. In the maximum deposition zone, infaunal biomass does not show any clear or consistent depression, but the community is conspicuously devoid of echinoderms and infaunal amphipods (Burd, 2003b; McPherson et al., 2007a).

In support of the monitoring program for the receiving environment of the Lions Gate Wastewater Treatment Plant Outfall located at 1st Narrows (Fig. 1), the Greater Vancouver Regional District has conducted annual biological monitoring in outer Burrard Inlet since 2002. Prior to that, historical data from the Inlet had been collected by Environment Canada (c.f. Boyd et al., 1998, and references therein) and the Department of Fisheries and Oceans (Burd and Brinkhurst, 1990; Cross and Brinkhurst, 1991; Burd, 1992; Je et al., 2003). Although the earlier work is not directly comparable to the GVRD monitoring due to differences in sampling protocols, a comparative assessment of the historical biotic conditions and geochemical sediment conditions of the outer Inlet was conducted by Burd (2004).

Both the deposition model of Hodgins et al. (2000) for the Lions Gate effluent solids and analysis of cores taken in 2004 (Burd, 2004) suggest that some material from the outfall is carried along the north shore of outer Burrard Inlet before settling offshore near the mouth of the inlet (Fig. 1). The model predicts that the remaining material will go into the inlet, past 1st

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Narrows (Inner Burrard Inlet), under specific tidal conditions, although sediment sampling has not confirmed this.

Unlike the receiving environment of the Iona Deep-Sea Outfall, where sediment chemistry and biota clearly show identifiable changes which can be directly related to the deposition of particulates from the outfall, no biotic changes which can be related to the discharge from the Lions Gate Outfall have been detected (McPherson et al., 2007b). This is partially because the outer Burrard Inlet is very well mixed and flushed (Thomson, 1981), and partially because there are numerous sources of anthropogenic discharge into the water body which can cause conflicting signals in sediment chemistry. Beyond First Narrows, the inner Inlet is particularly prone to the conflicting signals due to the greater intensity and frequency of various urban and industrial discharges than are found in the outer Inlet (GVRD, 2004). Sediment organic enrichment accompanied by sporadic elevated levels of typical sewage indicators or tracers (i.e. acid volatile sulphide, total organic carbon, sediment fecal coliforms, silver, 4-nonylphenol, coprostanol) do occur along the north shore of the outer inlet (McPherson et al., 2007b), with these effects decreasing with increasing distance offshore. Biotic changes in these areas have been noted, but are minor (McPherson et al., 2007b).

One location in the Burrard Inlet monitoring program, beyond First Narrows (in the inner inlet), has consistently shown more extreme organic enrichment and biotic impoverishment than any location in the outer inlet. Despite this, sewage indicators (e.g., silver, 4-nonylphenol and coprostanol) are not elevated, suggesting that sediment conditions are unlikely caused by the Lions Gate Outfall. Instead, combined sewer overflows are a potential source of the organic

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enrichment which could be related to the biotic changes in the inner harbour (GVRD, 2004), although multiple discharges in the area make it difficult to determine the source or sources.

A detailed analysis of sediment and outfall effluent metals data for 2002 and 2003 by Paine (2003 q.v. GVRD, 2004) suggested that elevated levels of some metals in outer Burrard Inlet are not likely related to the Lions Gate outfall, and are present at levels and in a form which should be biologically unavailable. Other metals are present below levels expected to cause any biological toxicity, based on Canadian Environmental Quality Guidelines (CCME, 1999).

Although technically not in the SoG, Victoria's Macaulay Point and Clover Point outfalls have been extensively studied and the long-term data on the benthos provide important context for similar habitats in the SoG. Also, despite the fact that the depth and current regime trap the plumes, suggesting that material from these outfalls is not likely to enter the SoG, there are times when the plumes have been known to surface so that any dissolved organics or contaminants in the upper water layer could enter through Haro Strait and eventually find their way to sediments in the SoG (Thomson, 1981) (also see Section 1.2). For that reason, information about the benthos near these two outfall areas is covered briefly below.

Victoria's Macaulay Point is an area of sandy substrate and high current that receives only screened (i.e. primary treatment) wastewater that is discharged at an approximate mean depth of 60-65 m. The Clover Point outfall in Victoria discharges at a similar depth but into a rocky, cobble environment that is dominated by a horse mussel (*Tressus tapyx*) community (Capital Regional District, 2000). Environmental monitoring of the benthic receiving environment at

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both of these major Victoria outfalls has been conducted since the early 1970s (Balch et al., 1973; 1975), with a revision of methods and quality control initiated in 2000 (http://www.crd.bc.ca/es/environmental _programs/wastewater_marine/macaulay/reports.htm). Numerous reports have been prepared by consultants on the results of this monitoring, along with annual monitoring reports (Capital Regional District, 2003, 2004, 2005; Paine, Ledge and Associates, 2004), along with a recent review of the Liquid Waste Management Plan and seafloor triggers by Stubblefield et al. (2006). Burd (2003c) reviewed the 1994 to 2001 data on benthic infauna and sediment geochemistry from the Macaulay Point outfall area and reported that the monitoring data show some faunal effects, but severe biotic degradation is not occurring in the vicinity of this outfall. Although, based on the available data, it is impossible to determine what toxic contamination effects may be important to the fauna of the receiving environment, the patterns of faunal change relative to the outfall strongly suggest that sediment geochemical changes and particle size are the predominant factors affecting faunal composition (Burd, 2003c). The sampling stations are situated radially around the outfall along a spatial gradient to 800m distant, with diminishing biotic and geochemical impacts to this distance in the E and SE (Burd, 2003c).

The biotic monitoring at the Clover Point outfall consists entirely of growth and condition factors for the dominant species, horse mussels. The hard substrates in this environment do not lend themselves to sediment sampling. Historically, the mussels within 800 m of the outfall tend to show a declining gradient of enhanced growth compared with reference locations (www.crd.bc.ca/wastewater/marine/ reports.htm).

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3.2 Ocean Disposal Sites

There are 11 designated ocean disposal sites regulated by Environment Canada in the SoG. Locations and annual dumping volumes for these sites are available at the Environment Canada website (http://www.pyr.ec.gc.ca/disposal_at_sea/sitemap_e.htm). The site also contains links to monitoring reports for all the sites over time. A brief overview of ocean dumping in BC is given in Ellis (1982), but there is almost no biological monitoring data from dumpsites in the SoG, except for the Point Grey dumpsite. Side-scan mosaicing has been proposed as an efficient method of monitoring new debris accumulation and dispersal at ocean disposal sites (Mosher et al., 1997).

The Point Grey disposal site, outside Burrard Inlet on the southeast side of the Strait, is the largest multi-user site in BC. This site has been in continuous use since the 1930s, and has been regulated by Environment Canada since 1975. Wilson and McKinnon (2003) reviewed the history, sediment and benthos monitoring data gathered for the Point Grey site from1975 through 2001. The site is between 230 and 250 m deep, with 80% of the sedimenting material from dumping and most of the remainder from the Fraser River discharge. In the late 1970s there was clear evidence of material from Burrard Inlet dumped outside of, *en route* to, the disposal site and evidence of this trail was still present in the early 1990s (see Mosher et al., 1997 and www.gsc.nrcan.gc.ca/marine_/gbgi/proj_ptgrey_e.php). In addition, detailed investigation of polycyclic aromatic hydrocarbon (PAH) signatures based on area-wide data suggested that recently dumped contaminants from Burrard Inlet were evident at the north end of the Iona outfall monitoring transect (80 m depth) in 2000 (Yunker, 2000; Yunker et al., 2000), well outside the ocean disposal boundaries.

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Benthic infaunal surveys were conducted periodically at the Point Grey disposal site (most recently in 1994) but sampling effort and taxonomic work varied considerably (Wilson and McKinnon, 2003). The accumulated material is presently significantly coarser than the surrounding area, probably due to winnowing and transport on the way to the bottom. Despite the limitations to interpretation imposed by taxonomic effort and quality control, and modification of substrates within the dumpsite, Wilson and McKinnon (2003) concluded that the Environment Canada monitoring data on benthic invertebrate biota did not show notable differences from biota found outside the dumpsite; for a guideline, the authors used the range in values expected within reference conditions for the Benthic Response Index (BRI) from the Southern California Coastal Water Research Project (SCCWRP). Unfortunately the BRI is based on local species-specific data, whereas the Point Grey biotic data were for different species identified only to the family level or higher, thus making extrapolation to the BRI problematic. Probably more convincing is the fact that on-going visual surveys (see below) show that the disposal site has historically been dominated by a range of polychaete taxa and had numerous burrowing and near-surface, echinoderms and amphipods, both of which groups are known to be sensitive to contamination and organic enrichment, as well as unusually high sedimentation (Burd, 2003b).

At the Point Grey disposal site, ROVs equipped with video and still cameras are used periodically to record images of the disposal site and the surrounding ocean floor (Wilson and McKinnon, 2003). Predetermined track lines plotted across the disposal site are followed by the ROV and continuous images of the ocean bottom are recorded. These visual images aid in the qualitative evaluation of the disposal site environment. ROV surveys show that the dumping of debris (e.g. logs, wire and construction materials) has created a more heterogeneous habitat than

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would normally be present at this depth, resulting in an artificially increased biodiversity of hard and soft substrate fauna.

3. 3 Pulp and Paper Mills

Macdonald et al. (1991) concluded that the pulp and paper mills in the SoG and surrounding fjords were contributing significantly to organic carbon input into the sediments of the Strait. Since then, the draft Pulp and Paper Effluent Regulations (PPER) were promulgated by Environment Canada in 1992, put into effect in 1996 and revised in 2004 (Regulations Amending the Pulp and Paper Effluent Regulations, (RAPPER), in order to reduce and control emissions (http://www.ec.gc.ca/nopp/pandp/en/p2004Letter. cfm). There are 6 operating pulp and paper mills which discharge effluent into marine subtidal habitats in the SoG and which are regulated by Environment Canada under the PPER. The mills in the Strait are shown in Fig. 1 (Crofton, Harmac, Elk Falls, Powell River and two in Howe Sound). Monitoring takes place from 30 m to 135 m depth and all but one of the mills discharge primarily into soft substrates ranging from 98% sand to 98% silt/clay (http://www.ec.gc.ca/EEM/English/PulpPaper /general.cfm). The Elk Falls mill discharges onto hard substrates and the Environmental Effects Monitoring (EEM) program for that mill focuses on invertebrate communities found in intertidal *Fucus* beds (www.ec.gc.ca/eem/English/PulpPaper/ data/showinfo.cfm?Mill_id=PP1122).

The current Environmental Effects Monitoring (EEM) program for the pulp and paper mills has now completed 3 cycles: 1996, 2000 and 2004. Data collection for cycle 4 is complete and reports have been submitted to Environment Canada but are not yet publicly available. The EEM program and technical guidance for monitoring are available at http://www.ec.gc.ca/EEM/

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English/PulpPaper/general.cfm, including the national database of benthic infauna and habitat conditions.

Results from Environment Canada's national synthesis reports available on the website show that although effluent quality from pulp and paper mills has vastly improved since initiation of the PPER (following the EEM cycle 1), effects on benthic invertebrates and fish are still observed. Some pulp and paper mill reports suggest that current effects on marine benthos are still related to historical deposition and that current inputs are much less of a problem. Aside from organic enrichment, the accumulation of wood fibre mats, organochlorines and dioxins/furans have been historical problems. Although the organic contaminants mentioned are now controlled (or banned) substances, their historical presence in these sediments suggests that they are still cycling through the food chain in the vicinity of pulp and paper mills.

The aforementioned synthesis reports further suggest that while eutrophication of the water column is the dominant factor affecting freshwater benthos exposed to pulp and paper mill effluent input, the typical response of biota in marine/estuarine benthic habitats is a decrease in abundance and richness of taxa that is more indicative of toxic, or smothering, effects (http://www.ec.gc.ca/EEM/English/PulpPaper /general.cfm). Near mill discharges, elevated C/N ratios (>15) are common while sediment sulphides are not particularly elevated in comparison, for example, with fish farm sediments (Burd, 2006). However, a re-examination of the EEM cycle 3 data from the SoG shows no trends in species richness or abundance related to distance from the discharge, sediment redox, sulphides, TOC or C/N ratio (Burd, unpublished data).

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However, there is some indication that taxa number and abundance decline with increasing depth, as found overall in the SOG data (Burd et al. in press; see Section 2).

Although the pulp and paper mills in the SoG appear to have no gross impact on subtidal infaunal benthos, this should not be interpreted to mean that the mills are not affecting the benthos; for example, quality control has never been standardized for the taxonomy of the pulp and paper mills marine EEM (technical guidance document http://www.ec.gc.ca/EEM/English/PulpPaper /general.cfm).

Environment Canada's EEM program for pulp and paper mills includes one mill site in the SOG which is predominantly hard substrate and is thus not amenable to the regular infaunal sampling methods recommended in the technical guidance. Data from the Elk Falls mill includes mixed studies of *Fucus* recolonization baskets in some cycles and standard beach quadrat surveys in others. The recolonization studies show a limited (rapid colonizing) species list of amphipods, isopods, and nemerteans that is missing the typical hard substrate species such as the molluscs and polychaetes, and larger predators (http://www.ec.gc.ca/eem/English/PulpPaper/data/showinfo.cfm?Mill_id=PP1122). The quadrat studies provide a species list much more typical of *Fucus* habitats as described in the Shorekeepers lists (http://www.shim.bc.ca/atlases/sk/main.htm). At present, these studies have not shown any gradient responses in biota to distance from the discharge. Based on research in the SoG, Bard (1998) describes biotic sensitivities and a proposed biotic index related to intertidal rocky beach fauna in areas affected by pulp mill effluent in BC.

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High organic loading from pulp mills and log boom areas is relatively refractory due to the slow rate of bacterial and invertebrate breakdown of organics. Therefore, the packing of dense debris typically causes severe sediment deoxygenation without dramatically elevated sulphides in sediments (http://www.ec.gc.ca/eem/english/PulpPaper/default. cfm; Samis et al., 1999). These areas may show a generalized depression of fauna (see Burd et al, in press), but be patchy, depending on deposition characteristics. The benthos may take a long time to recover in sediments with heavy wood-fibre mats due to the reduced and slow biotic activity, and sometimes low penetrability by burrowers.

3. 4 Log Booms

Areas of near-shore log booms are common along the SoG coastline. Log storage activities primarily impact low intertidal and shallow subtidal habitats within estuaries. Impacts include the physical shading of habitat by booms, leading to decreased primary productivity by algae and eelgrass (NEMP, 2002). At low tide, the physical grounding and abrasion by log booms result in compaction of sediments, scouring and physical disruption of habitats, particularly eelgrass beds (NEMP, 2002). Adjacent intertidal areas can be similarly impacted by escaped logs and propeller wash from tow boats can scour and increase the levels of suspended sediment in the water column (NEMP, 2002).

The working of logs against each other within the bundle results in deposition and accumulation of bark and wood debris on bottom sediments. These deposits are relatively refractory and the slow rate of bacterial and invertebrate breakdown can cause long-term stress to the benthic environment as a result of sediment deoxygenation, although sulphide levels are not dramatically

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elevated (http://www.ec.gc.ca/eem/ english/PulpPaper/default.cfm). General biotic effects may be similar to those described for pulp and paper receiving environments (Section 3.3), although the deposition of wood debris tends to be coarser and may be much heavier under log booms. McGreer et al. (1984) examined the recovery of an intertidal community in an area of the Nanaimo River estuary from which log booms had been removed. At 13 months after removal, common macro-invertebrate species were those typical of organic enrichment but the overall abundance was lower than that of the control area. The reduction in abundance was attributed to a shallow, but persistent, redox boundary at the log removal site. The effects of wood waste on near-shore sand beds (4-11 m) and associated fauna were studied by Conlan (1977) and Conlan and Ellis (1979), who found that deposition of >1 cm of wood debris caused notable faunal impoverishments, particularly in the suspension feeding fauna. Additional studies have suggested that wood debris may also inhibit the abundance of some infaunal bivalves (Burd et al., in press; Kathman et al., 1984; http://www.mareco.org/report/intro.htm). Kathman et al. (1984) examined the recolonization of settling trays in 15-20 m depth in outer Burrard Inlet, using different concentrations or wood waste from the Port Mellon pulp mill location in Howe Sound. After 11 weeks, they found that the 20% wood waste trays had a higher species diversity and lower dominance than found in the 0%, 50% and 100% wood waste trays, whereas abundance was equally high in the 20% and 100% trays. However, the 100% trays were dominated by nematodes, typical organic enrichment polychaetes and the wood-burrowing bivalve *Bankia setacea*. Other bivalves and polychaetes were abundant in the 0% and 20% trays, but rare in the 50% and 100% trays.

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A larger-scale examination of benthic responses to log-boom operations for the north coast of British Columbia, as well as Esquimalt Harbour (Victoria) is underway as part of a Ph.D. project (http://www.erf.org/cgi-bin/conference_abstract.pl?conference=erf2003% id+755).

3.5. Mine Tailings and Acid Mine Drainage

Between 1902 and 1974, the Britannia copper/zinc mine discharged 40 million tonnes of tailings into Howe Sound. Tailings were concentrated on the slope within 3 km of Britannia Beach but also covered most of the floor of the Sound's inner basin. During mine operations, subtidal sediments in areas deeper than 30 m had levels of copper and zinc that were considerably elevated above background (Levings and McDaniel, 1973, 1976; McDaniel, 1973), as well as above the current Probable Effects Levels for marine sediments (CCME, 1999). They also found that burial by the Squamish River sediment load and inputs from local creeks had diluted, or covered, the deposited tailings and reduced the metal concentration in surface sediments. Below sill depth (73 m), waters in Howe Sound tend to be seasonally anoxic, limiting not only the mobility of metals from the sediments but also the biodiversity and abundance of benthic fauna, regardless of tailings (Levings et al., 1983). Several studies in the 1970s focused on the effects of deposition of metals and tailings from the active Britannia Mine operation on the macrobenthos (Levings and McDaniel, 1973; McDaniel, 1973; Levings and McDaniel, 1976), but based on more recent studies near Brittania (Ellis and Hoover, 1990) and on long-term recovery of sediments affected by tailings from mines located outside the SoG in British Columbia (Burd et al., 2000b; Burd, 2002), it is assumed that the deep benthos has recovered some 30 years after cessation of tailings deposition. However, it is also clear that considerable acid mine drainage is still leaching out into the near shore area around the historical Britannia

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mine. Recent studies confirm impacts on near shore fish and fish habitat (for an overview, see Hagan et al., 2004). In addition, Grout and Levings (2001) examined the effects of acid mine drainage on intertidal mussels in the area and showed that caged and ambient mussels were adversely affected by elevated tissue copper levels to a distance of about 2 km N and S of the discharge creek. In December 2001, the acid mine drainage was diverted to an outfall at 30 m depth into Howe Sound. Zis et al. (2004) looked at the intertidal community recovery at Britannia Beach after diversion, and found that some, but not total recovery was evident in invertebrate species number and abundance, as well as transplanted mussels. The authors concluded that some continued seepage from the old mine was still inhibiting normal growth and survival in the intertidal area. G3 Consulting (2003) provided a report on the shallow subtidal (<30 m depth) biota, sediment metals and organics from the foreshore around the Brittania mine. Levings et al. (2004) describe the toxicity of the acid mine drainage to estuarine organisms from the discharge creek, noting that invertebrate food resources for juvenile salmonids in the intertidal near the drainage creek were adversely affected by the acid mine drainage.

3.6 Aquaculture

In BC, the majority of the finfish aquaculture industry in the inside waters is located north of the SoG; there are only a few salmonid farms at the south end of Johnson Strait (the north end of the SoG) and in some of the contiguous mainland fjords. Where organic deposition is excessive, and fauna have declined, reactive organic detritus may be present in a labile state as a flocculent layer on the sediment surface (Kristensen, 1988). Fish farms provide an example of an organic source with minor copper (antifoulants) and zinc (feed) contaminants (c.f. Brooks 2001). Studies of benthic faunal patterns and recovery at the few marine mine tailings deposition sites,

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however, suggest that particulate levels of these metals typically found under fish farms do not seem to have a notable effect on infaunal benthos in the deeper subtidal, despite the fact that bivalves, in particular, can accumulate metals (Burd et al., 2000b; Burd, 2002). Rather, zinc and copper levels are typically used as deposition tracers around fish farms (Yeats, 2002).

The organic deposition in the vicinity of fish farms tends to be highly labile, as compared to wood fibre waste or other organic materials. Hence, the organic material tends to be broken down relatively quickly (e.g. in comparison to wood fibre debris) and recovery proceeds at a measurable pace. The effects of this highly labile deposition include sediment de-oxygenation and hydrogen sulphide accumulation which lead to the enrichment of some taxa such as the opportunistic polychaete *Capitella capitata* complex that are tolerant of these conditions and the impoverishment of sensitive taxa. At fish farms where organic enrichment loads are high and sediment geochemistry includes low oxygen levels and high sulfide accumulation (i.e. ~6000 μm), tolerant and opportunistic polychaete species tend to dominate on soft substrates and on hard substrates where sedimentation occurs, whereas most other fauna disappear under these extreme conditions (Brooks, 2001; Burd, 2006; Hargrave et al., 2008). However, some epifaunal crustaceans typically found in detritus mats nearshore may thrive in the debris mats under the net cages (Burd, 2006).

Under more moderate sulphide buildup conditions (1700-3000 μM), a variety of organism types may be present, but Burd (2006) show that some biotic impoverishments are highly likely, along with a potential proliferation of opportunistic polychaetes. In particular, echinoderms and infaunal crustaceans appear to be highly sensitive to organic enrichment conditions in sediments (Burd, 2006; McPherson et al., 2007a). On hard substrates, some cnidarians (such as *Metridium*

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senile) may be opportunistic under moderate organic enrichment conditions, but echinoderms will still be absent, as will larger sponges (Emmett et al., 2005; 2006; 2007), due primarily to excessive deposition, and/or near-bottom low oxygen conditions. Where organic loading is elevated, but within the assimilative capacity of the sediments, a biotically-enriched community may be present (Burd, 2006; Brooks, 2001). Recent reviews of biotic effects related to fish farms in BC are given in Brooks (2001),Burd (2003a; 2006) and Hargrave et al. (2008). Some important information on general sediment sulphide tolerance of common BC species is available in Brooks (2001).

A large number of beach and near-shore shellfish aquaculture sites are located in Baynes Sound on the east coast of Vancouver Island. Carswell et al. (2006) describe an aerial survey method that has been used to show that >20% of the intertidal zone of the sound is occupied by shellfish tenures. A review of the available literature and monitoring data related to potential impacts from shellfish culture for the intertidal areas of Baynes Sound is given in Jamieson et al. (2001). To date, studies show that the benthic impact of deep-water suspended culture of Pacific oysters appears to vary depending on the specifics of the site, including hydrography, bathymetry and natural deposition rates and sediment characteristics (Barnes, 2006). Regardless, data revealed that the benthic invertebrate communities in close proximity to the shellfish farms showed no reduction in either faunal abundance or diversity (Barnes, 2006). In Baynes Sound, an area of the SoG heavily tenured by shellfish leases, Bendell-Young (2006) studied three geographically similar clam farm beach sites, along a farming intensity gradient (fallow, 3 years active, 5 years active). In contrast to the fallow site, the 3 and 5 year active sites had intertidal regions with heavier silt and organic matter, lower species richness and increased domination by bivalves. However, a geographically more diverse study, including a site on the west coast of Vancouver

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Island, found that clam density on netted farm sites was significantly greater than on reference sites only in the low intertidal and that this significant increase in total clam density mirrored the increase in 1 species of bivalve, *Venerupis philippinarum*, in this stratum at farm sites (Whiteley and Bendell-Young, 2007). The study also demonstrated that bivalve species composition was not significantly different between farms and reference sites, suggesting that predator nets did not effectively change the structure of the infaunal communities at these sites. Farm sites were more similar to each other as a group than reference sites, however, and the authors suggest that this may lead to a loss of the regional distinctness that was evident among the reference sites (Whiteley and Bendell-Young, 2007).

3.7 Bottom Trawling

In near-shore coastal areas such as the SoG, bottom trawling is likely to result in physical disturbance. Bottom trawling can have devastating effects on bottom infaunal and epifaunal communities in other coastal areas (Watling and Norse, 1998). For example, otter trawling on soft bottoms has been found to significantly reduce the abundance of most invertebrate taxa (Engel and Kvitek, 1998; and other papers in Conservation Biology issue 12: Vol. 6). Effects on the benthos range from crushing, burying and dislocation of fauna, to habitat destruction and resuspension of fine particulates into a turbid boundary layer. Such practices can also damage nursery grounds or bottom fish stock. Various studies report a reduction in organism abundance and species richness $\geq$50%, and substantial reductions in biomass (for review, see Watling and Norse, 1998). The effects of bottom trawling do not resemble any of the contaminant impacts described in the literature (Burd 2003b; Cook et al., in press), and arguments have been made that certain refugia such as the sponge reefs in the Strait should be protected from bottom

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trawling (Conway et al., 2007). Unfortunately, there is virtually no concurrent spatial or temporal information on the combined, or synergistic, biotic effects of contaminant discharges and bottom trawling in the SoG.

3.8 General Contaminants Loadings (non-point source)

There are numerous sources of contaminants entering the SoG, particularly originating from, or as a result of, the highly urbanized centers near the BC/Washington border. Aside from localized surveys of sediment contaminant loadings related to specific discharges (see references in above sections 3.1 to 3.7 related to monitoring programs for site-specific discharges), there have been a few broader-scale studies of certain contaminants of concern or tracers of discharge types, focusing on their distributions and budgets (c.f. Macdonald et al., 1991,1992 – Pulp mills; Gordon,1997 – silver; Shang et al., 1999 – nonylphenols; Yunker et al., 1999 – PAHs; Johannessen et al. 2005a – Mercury; Johannessen et al. in press – PCBs/PBDEs). In addition, the potential for development of bottom water and sediment hypoxia from organic loading have been discussed using organic carbon budgets (Johannessen et al., 2003), and evaluation of sediment organic/oxygen conditions based on redox chemicals in cores (Macdonald et al., in press).

Sediment guidelines and all the studies that have contributed to their development (CCME, 1999; BCWQO;http://www.env.gov.bc.ca/wat/wq/BCguidelines/approv_wq_guide/approved.html) provide some guidance related to possible responses of benthic invertebrate fauna to contaminants of concern. However, field validation of these hypothetical tolerances and responses is lacking for SoG fauna.

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4. Conclusions

Although there is considerable descriptive information pertaining to invertebrate benthos (largely unpublished) of the SoG, quantitative evaluations are much less abundant and patchy spatially and temporally. Burd et al. (in press) provide a comparative assessment of infaunal biomass, species richness, and abundance measures which can be reasonably predicted by measurements of organic quality and flux to sediments in the SoG. Results are also dependent on the source and relative quantity of inorganic flux, with areas influenced by the Fraser River discharge providing apparently more productive substrate for macro-invertebrates than marine depositions. With a broader scale understanding of sediment organic and inorganic sources and fluxes in the SoG, it may be possible to begin to model and ground-truth subtidal benthic productivity of the SoG. This would also require a clearer understanding of how the smaller invertebrate groups (meiofauna) and microfauna respond to sediment organic and inorganic fluxes. The next logical step would be to interpret sediment productivity in the context of budgets/models of sediment contaminants, organic inputs and redox conditions for the SoG. In addition to understanding how benthic organisms may be affected by contaminant and organic loading on a regional scale, the potential for bio-accumulation and trophic transfer of contaminants of concern needs to be studied for the bottom-dwelling portion of the subtidal food chain. Predicting the effects of on-going climate changes will also require an understanding of how the sessile components of the benthic ecosystem are likely to change in response to major sedimentation shifts or events.

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Figure Captions

Figure 1. The Strait of Georgia, including depth contours from multibeam imagery (see also Fig. 3), locations of important geographic units and discharge sources described herein, and theoretical boundaries of north, middle and southern oceanographic regimes within the main basin.

Figure 2. Physical parameters used to develop ecounits (Modified from the Ministry of Sustainable Resource Management (http://ilmbwww.gov.bc.ca/risc/). Substrate = mud, sand, hard (M,S,H); Exposure = high, moderate, low (H,M,L); Current = High >3knots, low<3 knots (H,L); Slope = Flat 0-5%, sloping 5-20%, Steep >20% (F,S,S); Depth = Shallow 0-20m; photic 20-50m, mid-depth 50-200m, deep 200-1000m; Temperature = warm 9-15°C, cold <9°C; Relief = low 0-1, medium 2, high 3-4. For example: ecounit = M/L/L/F/M/C/L: Substrate = mud; Exposure = low; Current = low; Slope = flat; Depth = mid-depth; Bottom Temperature = cold; Relief = low.

Figure 3. Multibeam imagery from the southern Strait of Georgia showing bottom relief and type, courtesy of Natural Resources Canada, Pacific Geoscience Center, Sidney, BC.

Figure 4. Plot of sediment percent fines (silt/clay <63 μm particle size) to illustrate sediment types in the Strait of Georgia (data from Burd, 2006; and courtesy of Natural Resources Canada, Pacific Geoscience Center, Sidney, BC).

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Figure 5. MERIS satellite taken 2007/07/10 (copyright, European Space Agency). True colour image, Courtesty of Jim Gover and Stephanie King, Institute of Ocean Sciences, Canadian Department of Fisheries and Oceans, Sidney, BC.

Figure 6. Shorekeepers' Program sites in the Strait of Georgia, BC. (http://www.shim.bc.ca/atlases/sk/main.htm).

Figure 7. Habitat (beach) suitability maps for Pacific oysters and Manila clams and a corresponding area map for kelp and eelgrass habitat as generated by the Internet. Framework Mapping tool provided by the Provincial Ministry of the Environment (http://maps.gov.bc.ca/).

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Table 1. Gross features of the Strait of Georgia, B.C. (from England et al. 1996, Thomson 1998, and Thomson and Foreman 1998).

Feature	**Measure**
Surface Area	6515 km^2
Area at 100m depth	4374 km^2
Volume	1050 km^3
Mean Depth	155m
Maximum Depth	420m (S Texada Island)
Annual Mean Runoff	5650±3500 m^3/s
Drainage Area	286,890 km^2
Sill Depth – Haro Strait	90m
Sill Depth – Rosario Strait	50m
Summer Basin Flushing	50-75 days
Winter Basin Flushing	100-200 days

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3316 Figure 1

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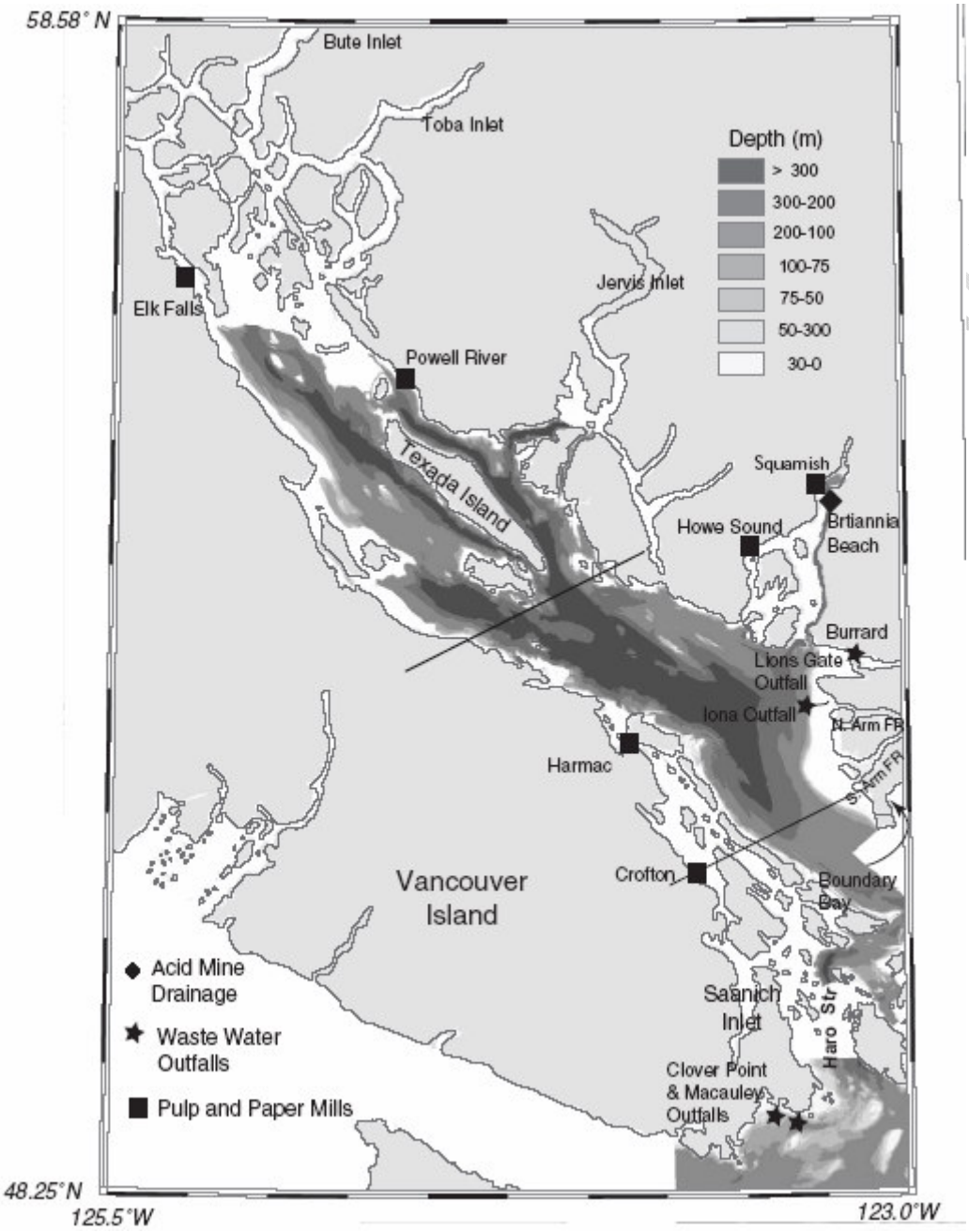

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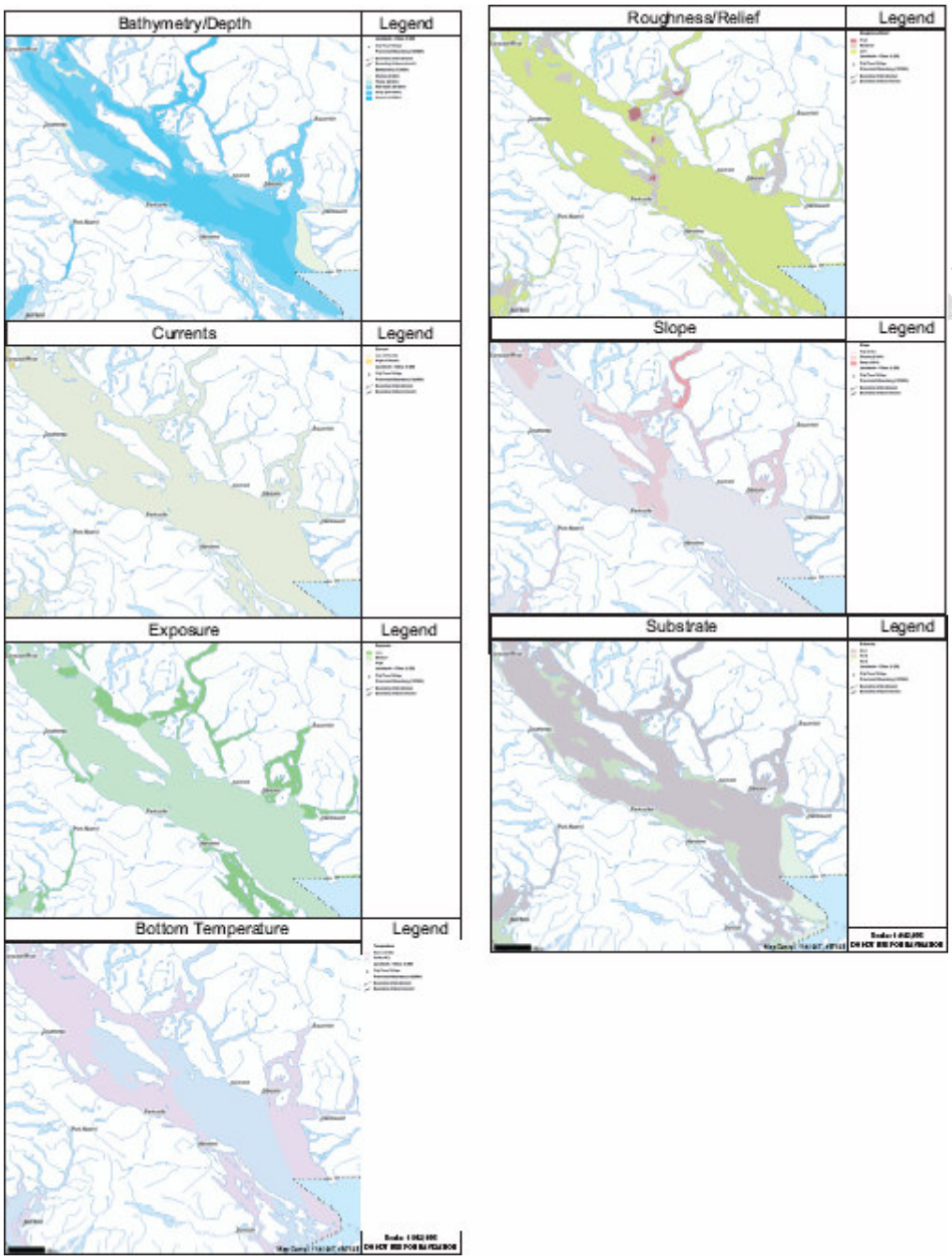
Figure 2



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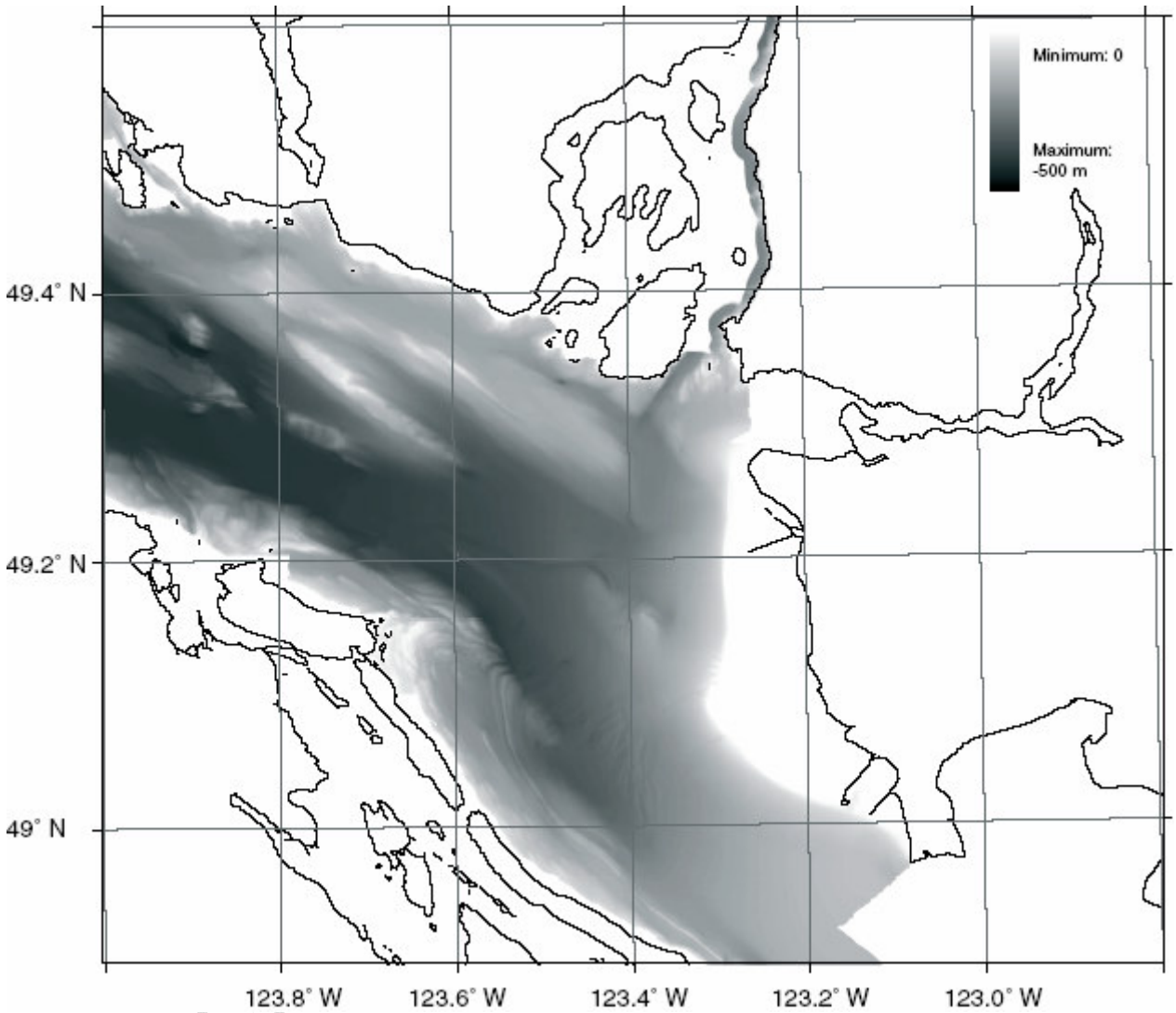

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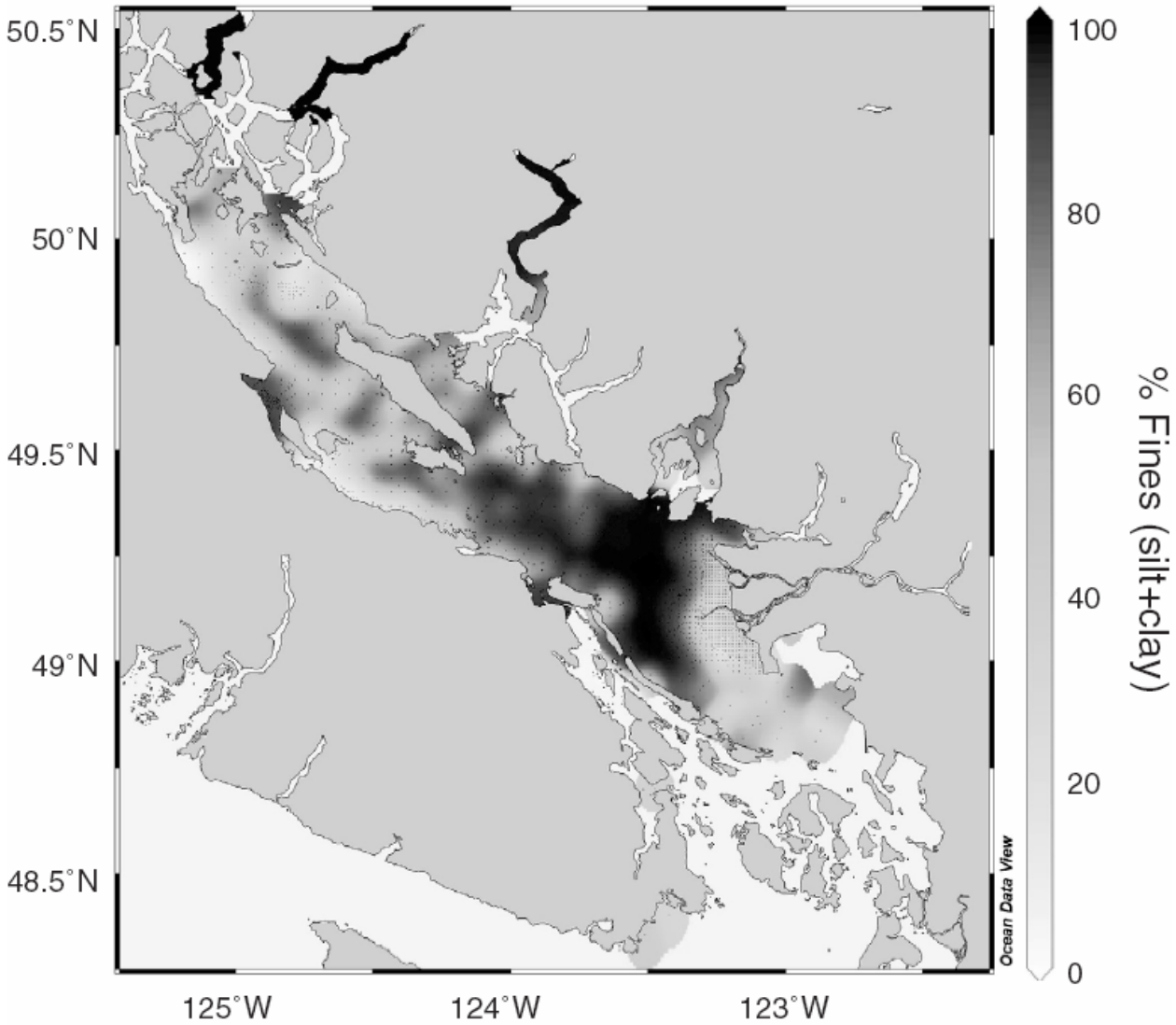

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Figure 5

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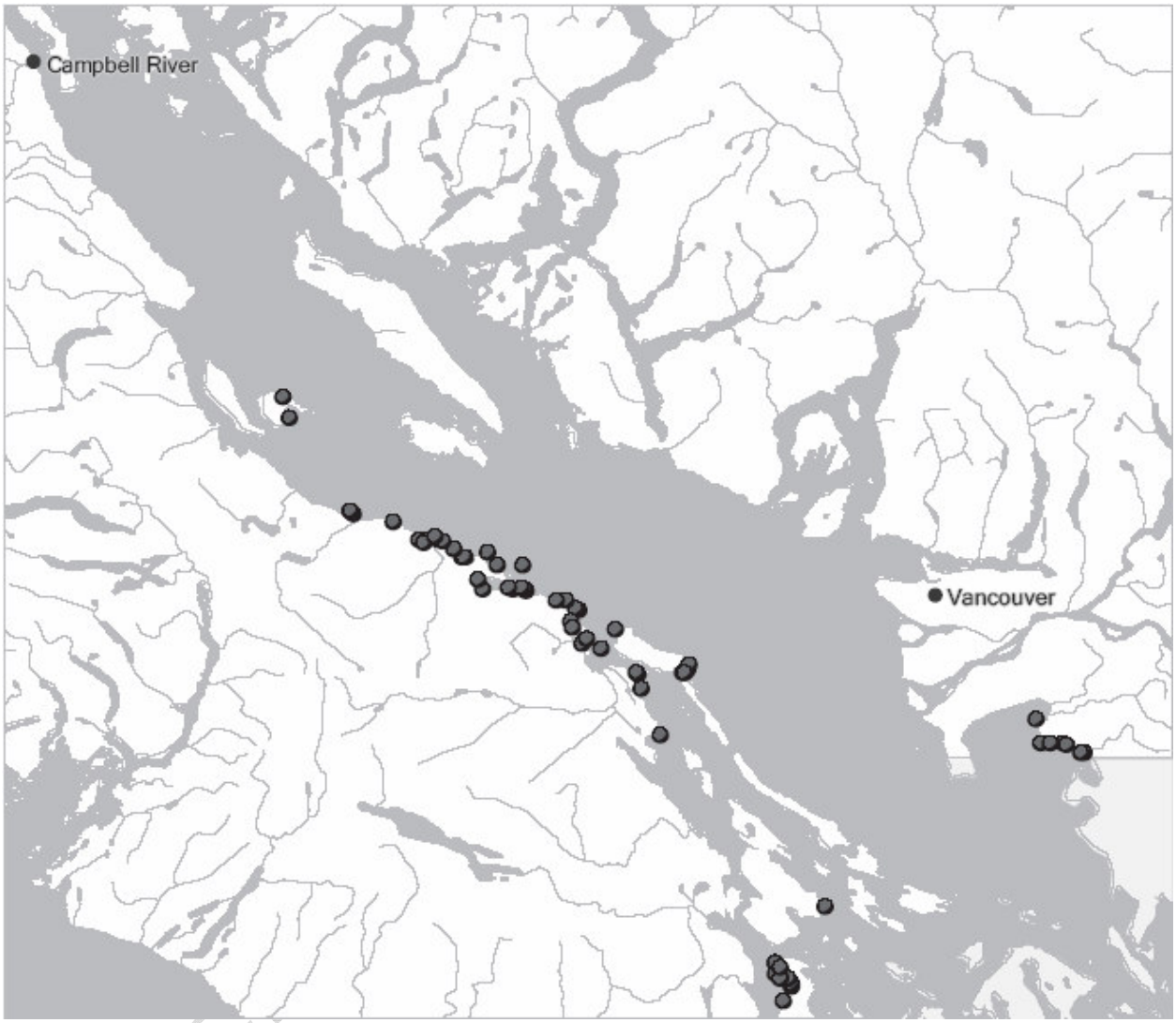
Figure 6



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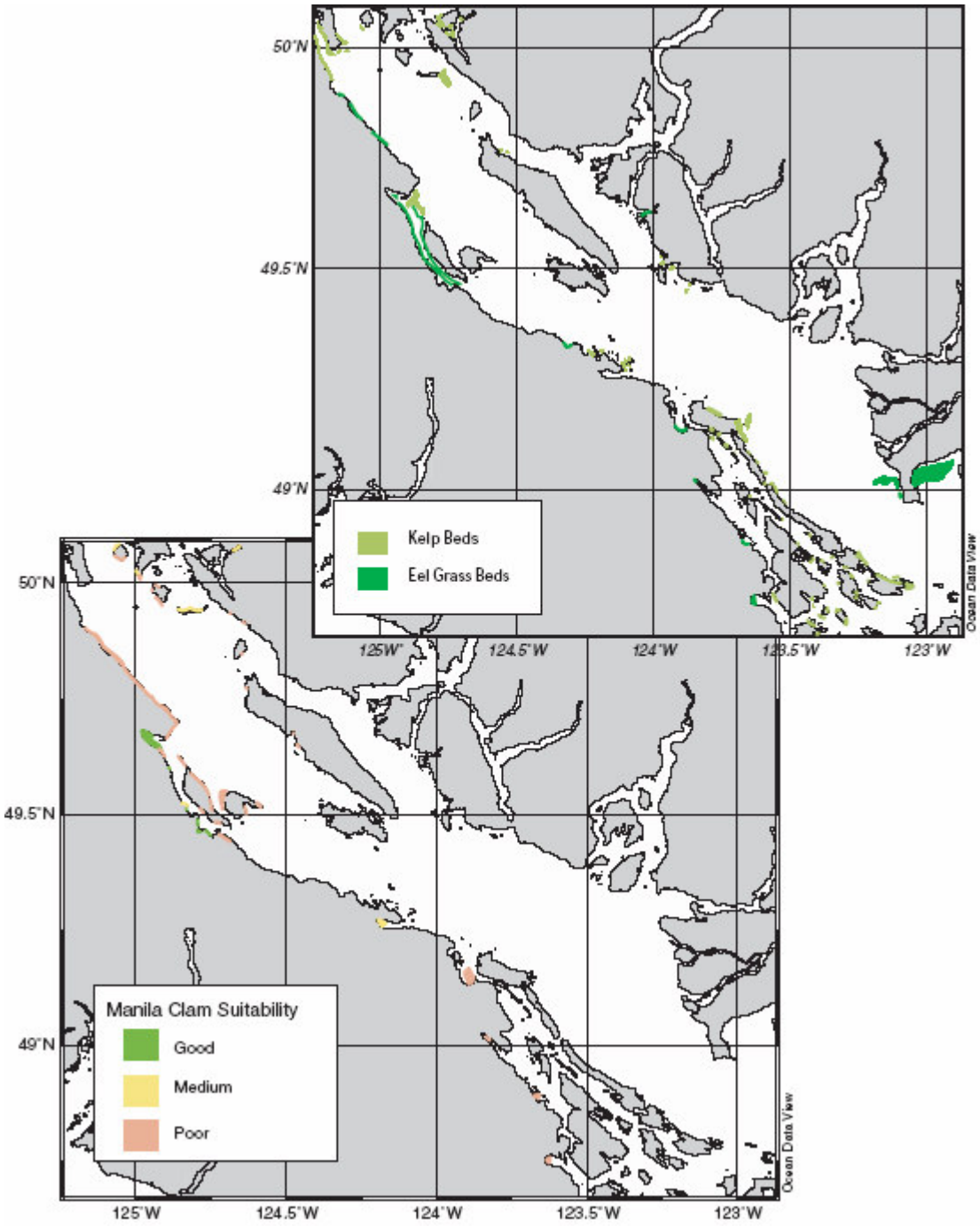
Figure 7